2021-06

IMPROVING MANAGEMENT OF COMMERCIAL SATELLITE MEGA-CONSTELLATIONS

Yoo, Brian

Monterey, CA; Naval Postgraduate School

http://hdl.handle.net/10945/67837

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

IMPROVING MANAGEMENT OF COMMERCIAL SATELLITE MEGA-CONSTELLATIONS

by

Brian Yoo

June 2021

Thesis Advisor: Craig M. Boucher
Second Reader: Scott P. Simmons

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2021	**3. REPORT TYPE AND DATES COVERED** Master's thesis	
4. TITLE AND SUBTITLE IMPROVING MANAGEMENT OF COMMERCIAL SATELLITE MEGA CONSTELLATIONS			**5. FUNDING NUMBERS**
6. AUTHOR(S) Brian Yoo			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

Large commercial satellite constellations, colloquially nicknamed "mega-constellations," are providing improved capabilities for satellite operators and enhanced services for terrestrial users. While so, the environment in which these large space architectures operate, low Earth orbit, is cluttered with active satellites and littered with orbital debris. If not properly managed, commercial satellite mega-constellations could worsen the space environment for all space operators as they inherently involve more satellites and thus more risk. This thesis examines the United States' management of commercial satellites in three segments: pre-launch, on-orbit, and post-mission. This thesis further analyzes the entities, documents, and processes involved in the U.S. management of commercial satellites and identifies areas of concern raised by the looming rise of commercial satellite mega-constellations. Recommended improvements to the management framework address these concerns and discuss the (1) implementation of "core safety minimums," (2) establishment of rules for day-to-day satellite operations, (3) establishment of a set of core definitions and standards, (4) establishment and empowerment of a national entity for space situational awareness and space traffic management, (5) incentivization of post-mission disposal, and (6) reduction of post-mission orbit lifetime limits for expended satellites in decaying satellites.

14. SUBJECT TERMS United States, U.S., management, satellite, mega-constellation, large, pre-launch, on-orbit, post-mission, policy, low Earth orbit, LEO, space situational awareness, SSA, space traffic management, STM, post-mission disposal, PMD			**15. NUMBER OF PAGES** 123
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

**IMPROVING MANAGEMENT OF
COMMERCIAL SATELLITE MEGA-CONSTELLATIONS**

Brian Yoo
Lieutenant, United States Navy
BS, U.S. Naval Academy, 2015

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS

from the

**NAVAL POSTGRADUATE SCHOOL
June 2021**

Approved by: Craig M. Boucher
Advisor

Scott P. Simmons
Second Reader

James H. Newman
Chair, Space Systems Academic Group

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Large commercial satellite constellations, colloquially nicknamed "mega-constellations," are providing improved capabilities for satellite operators and enhanced services for terrestrial users. While so, the environment in which these large space architectures operate, low Earth orbit, is cluttered with active satellites and littered with orbital debris. If not properly managed, commercial satellite mega-constellations could worsen the space environment for all space operators as they inherently involve more satellites and thus more risk. This thesis examines the United States' management of commercial satellites in three segments: pre-launch, on-orbit, and post-mission. This thesis further analyzes the entities, documents, and processes involved in the U.S.'s management of commercial satellites and identifies areas of concern raised by the looming rise of commercial satellite mega-constellations. Recommended improvements to the management framework address these concerns and discuss the (1) implementation of "core safety minimums," (2) establishment of rules for day-to-day satellite operations, (3) establishment of a set of core definitions and standards, (4) establishment and empowerment of a national entity for space situational awareness and space traffic management, (5) incentivization of post-mission disposal, and (6) reduction of post-mission orbit lifetime limits for expended satellites in decaying satellites.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

18 SPCS	18th Space Control Squadron
ADR	active debris removal
AGI	Analytical Graphics, Inc.
ASAT	anti-satellite
AST	Office of Space Transportation
CA	conjunction assessment
CAN	close approach notification
CARA	Conjunction Assessment Risk Analysis
CDM	conjunction data message
CFR	Code of Federal Regulation
CME	coronal mass ejection
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
COPUOS	Committee on the Peaceful Uses of Outer Space
CRS	Congressional Research Service
CRSRA	Commercial Satellite Remote Sensing Regulatory Affairs
DAMAGE	Debris Analysis and Monitoring Architecture to the Geosynchronous Environment
DEL 2	Delta 2
DOC	Department of Commerce
DOD	Department of Defense
DOI	Department of the Interior
DOS	Department of State
DOT	Department of Transportation
eGP	extrapolated general perturbation
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
GEO	geosynchronous Earth orbit
GPS	Global Positioning Service
HAC	High Accuracy Catalog

IADC	Inter-Agency Space Debris Coordination Committee
IDA	Institute for Defense Analyses
IMS	International Monitoring System
IOC	International Orbital Debris Conference
ISS	International Space Station
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union Radiocommunication Sector
LED	light emitting diode
LEO	low Earth orbit
LTS	long-term sustainability
MEO	medium Earth Orbit
NAPA	National Academy of Public Administration
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
O/O	owner/operator
OD	orbit determination
ODR	orbital data request
OECD	Organization for Economic Co-Operation and Development
OES/SA	Bureau of Oceans and International Environmental and Scientific Affairs
OSC	Office of Space Commerce
Pc	probability of collision
PMD	post-mission disposal
RR	Radio Regulations
REG	Registration Convention
RF	radio frequency
RFI	radio frequency interference
RPO	rendezvous proximity operations
RSO	resident space objects
SDA	Space Data Association
SDTC	search, discover, track, and characterize

SIA	Satellite Industry Association
SOA	Space Operations Assurance
SOAC	Space Operations Assurance Consortium
SP	special perturbation
SPD	Space Policy Directive
SSA	space situational awareness
SSC	Space Safety Coalition
SSN	Space Surveillance Network
STM	space traffic management
TCA	time of closest approach
TLE	two-line element
UN	United Nations
USAF	U.S. Air Force
USG	U.S. Government
USGODMSP	U.S. Government Orbital Debris Mitigation Standard Practices
USSF	U.S. Space Force

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

Among all of Earth's orbital regimes, low Earth orbit (LEO), cluttered with active satellites and littered with orbital debris, is by far the most congested [1]. As economic opportunity demands, however, the commercial space industry continues to launch satellites into LEO and, now, at a rapid pace due to the growing use of commercial satellite mega constellations. While these large space architectures undoubtedly improve services in communications and remote sensing, they raise risk in the LEO environment as they involve hundreds to thousands of networked satellites [2]. If left inappropriately managed, commercial satellite mega-constellations could worsen the space environment for all space operators [3]. Although this concern affects all nations, the international community has been largely unable to reach consensus on acceptable space behaviors and activities [4]. As one of the world's leading spacefaring nations and the nation that possesses the largest commercial satellite mega-constellation [5], the United States must take the initiative and establish a standard for other spacefaring nations to follow.

To this effort, this thesis addresses how the United States government (USG) could improve commercial satellite mega-constellations management to ensure LEO's sustainability and safety while also growing the commercial space industry. Although the current management framework does not appropriately address commercial satellite mega-constellations, this thesis examines the entities, documents, and processes involved in the pre-launch, on-orbit, and post-mission management of commercial satellites. In addition, this thesis identifies areas of concern raised by commercial satellite mega-constellations and offers improvements to the U.S. management framework. As this thesis reveals, the main challenge facing the management of commercial satellite mega-constellations is the lack of national-level oversight and verbiage specifically for these massive space architectures. As commercial satellite mega-constellations inherently involve more satellites and satellite operators, the potential for accidents can grow significantly [2] if left inappropriately managed. This fact becomes apparent in all three segments of commercial satellite management.

In the pre-launch management of commercial satellites, entities and processes largely focus on launch, communications, remote sensing, and, more recently, orbital debris mitigation requirements. However, the rise of commercial satellite mega-constellations now need pre-launch management entities and processes to incorporate minimum safety features for satellites that improve on-orbit safety (i.e., satellite maneuverability) and management activities (i.e., satellite trackability). Therefore, the USG should employ the Department of Commerce's Office of Space Commerce (OSC) in implementing "core safety minimums" that include propulsive capabilities and passive or active means of trackability.

In the on-orbit management of commercial satellites, there is a significant lack of a governing presence for commercial satellites. There remains an absence of rules for the day-to-day operations of satellites and a governing set of core definitions and standards for on-orbit management activities. Furthermore, there is an absence of dedicated, empowered, and authoritative entities for national space situational awareness (SSA) and space traffic management (STM). Ushering in a large number of active satellites into LEO, commercial satellite mega-constellations now necessitate the on-orbit management architecture to evolve and appropriately address the looming increase of satellites, operators, and risk. As such, the USG should employ the OSC to establish a basic body of space traffic rules and a set of core definitions and standards for on-orbit management activities. In addition, Congress must improve the formalization and empowerment of the OSC to enable it to effectively act as the nation's focal point for commercial SSA and STM.

In the post-mission management of commercial satellites, there is a lack of active enforcement for post-mission activities and an adequate post-mission lifetime limit for satellites with decaying orbits. With the increasing pace at which commercial satellites launch [1] and de-orbit as a result of commercial satellite mega-constellations, the USG should consider new alternatives for enforcing post-mission disposal (PMD) and preventing collisions caused by decaying objects. Therefore, the USG should designate the OSC as the national entity for incentivizing PMD, perhaps through a point system, and should reduce the post-mission orbit lifetime limit from 25 years to 1 year.

In all three management segments, the USG/OSC must leverage and collaborate with the commercial space industry, especially satellite operators, to effectively improve the management of commercial satellite mega-constellations. The commercial space industry provides a wealth of knowledge, experience, and insight regarding space operations which will be significantly valuable for evaluating the feasibility of proposed improvements. Close coordination with the commercial space industry can better ensure that improvements are promulgated and implemented efficiently and effectively.

Lastly, improved management of commercial satellites and mega-constellations cannot be exclusive to the United States. Due to the fact that the international community remains unable to reach consensus on requirements for space activities [3], it may be more effective to provide the international community with a functioning management framework that pursues improving sustainable and safe space operations as well as growth of its commercial space industry. Such a management framework can likely be enticing for many, if not all, spacefaring nations to adopt. Therefore, the USG, as one of the world's leading nations in space, must take the initiative and ensure that improvements to its management framework are transferable to other spacefaring nations. This means genuinely pursuing sustainable and safe space operations as well as growth of the commercial space industry. This also includes avoiding improvements that leverage or require excessive costs and technologies that only the United States can satisfy. Afterall, space is inherently an international domain where one accident affects all.

References

[1] M. Dominguez, M. Faga, J. Fountain, P. Kennedy, and S. O'Keefe, "Space traffic management: assessment of the feasibility, expected effectiveness, and funding implications of a transfer of space traffic management functions," National Academy of Public Administration, Washington, DC, USA, 102252, Aug. 2020. [Online]. Available: https://s3.us-west-2.amazonaws.com/napa-2021/studies/united-states-department-of-commerce-office-of-space-commerce/NAPA_OSC_Final_Report.pdf

[2] P. Chrystal, D. McKnight, and P. L. Meredith, "New space, new dimensions, new challenges: how satellite constellations impact space risk," *Swiss Re Corporate Solutions Ltd*, Jul. 17, 2018. [Online]. Available: https://www.swissre.com/Library/how-satellite-constellations-impact-space-risk.html

[3] M. A. Hallex and T. S. Cottom, “Proliferated commercial satellite constellations: implications for national security,” *Jt. Force Q.*, vol. 2nd Quarter, no. 97, pp. 20–29, Apr. 2020.

[4] J. C. Moltz, *Crowded Orbits: Conflict and Cooperation in Space*. New York: Columbia Press University, 2014.

[5] C. Henry, “SpaceX becomes operator of world’s largest commercial satellite constellation with Starlink launch,” *Space News*, Jan. 06, 2020. https://spacenews.com/spacex-becomes-operator-of-worlds-largest-commercial-satellite-constellation-with-starlink-launch/

I. INTRODUCTION

A. OVERVIEW

Among all of Earth's orbital regimes, low Earth orbit (LEO), generally defined as the region in space between ~160 to 2,000 km in altitude [1], is by far the most congested. As the closest to Earth and therefore the cheapest to reach, LEO is the most popular orbital regime for satellite deployments [2]. Resultingly, decades of the world's space activities have left LEO cluttered with active satellites and littered with orbital debris [3]. Yet, on 2 May 2021, SpaceX placed another 60 Starlink satellites in LEO, expanding the world's largest commercial constellation with the presence of nearly 1,500 satellites [4], [5]. A satellite constellation is a "number of similar satellites, of a similar type and function, designed to be in similar, complementary, orbits for a shared purpose, under shared control" [6]. While large commercial satellite constellations like SpaceX's Starlink undeniably offer tremendous potential for the satellite industry [7], they inevitably increase the probability of "mutual collisions among orbiting objects" [8] due to the inherently high number of satellites involved in large constellations. From potentially disrupting space traffic management efforts to catalyzing collision cascades [8], the massive influx of satellites expected to enter LEO by way of large commercial satellite constellations poses a significant threat to the sustainability and safety of space operations.

B. BACKGROUND

The challenges currently facing the management of large commercial satellite constellations primarily derive from three significant trends in space: (1) the commercialization of space, (2) the proliferation of commercial satellite mega-constellations, and (3) the growth of orbital debris. While these trends do not exclusively contribute to the increasing difficulty of managing large commercial satellite constellations, they collectively provide foundational knowledge that appropriately frame the context for current and future challenges.

1. Commercialization of Space

Over the last decade, the space domain has seen a significant transition from "old space" to "new space" wherein the realm once solely dominated by powerful governments has revolutionized into a widely accessible commercial market [9]. While there are several terms that describe this shift (e.g., democratized space or Space 2.0 [10]), these terms generally describe the nearly explosive emergence of "a decentralized set of space companies" [2] that has revitalized the U.S. space industry through "faster and cheaper access to space, distinct from more traditional government-driven activities focused on security, political, or scientific activities" [10]. Rapid advances in technology and manufacturing capability have enabled more advanced and smaller sized satellites to deploy into space at lower costs [9]. As a result, these factors have ushered in a wave of new commercial space entities that are now conducting activities historically reserved solely for governments that could overcome "high fixed-cost barriers to entry" [2]. Today, the commercialization of space is evident both qualitatively and quantitatively where trends such as the growth in density and diversity of commercial space entities as well as the growth in the space economy have unequivocally signified the commercialization of space.

Qualitatively, the commercialization of space is observable in the substantial presence of non-governmental space entities within today's space community. Lowered barriers to enter the space domain such as reduced costs for space launches [11] and increased capabilities in the mass production of smaller, lighter, and cheaper spacecraft [2], [9] have ushered in numerous new commercial "participants than was historically possible" [10]. Such participants include companies like SpaceX, OneWeb, LeoSat, and Kepler Communications, among others. In turn, these commercial space entities have further reduced costs and brought new products as well as services to the market [2]. As described by the National Academy of Public Administration (NAPA) in an August 2020 report, "commercial space companies as well as those that provide services and products to space agencies have sped up development cycles and reduced the costs of activities such as rocket launches, space situational awareness, on-orbit servicing, and space exploration" [2].

Today, numerous commercial space entities offering various services exist: (1) "space access" companies that launch people and payloads into space, (2) "remote sensing" companies that provide imaging and monitoring of the Earth, (3) "satellite data and analytics" companies that provide spacecraft information and analyses [2], and (4) "communications" companies that provide digital connectivity around the globe [11]. More recently, the commercial space industry has begun to see the entrance of entities that provide even more services such as (5) "habitats and space stations" companies that will offer "facilities for manufacturing, research, and even tourism" in space and (6) "beyond low Earth orbit" companies that intend to conduct a variety of missions from asteroid mining to the colonization of the Moon and Mars [2]. Table 1 provides examples of current and planned commercial space activities and entities.

Table 1. Examples of Current and Planned Commercial Space Activities. Source: [2].

Activity Type	Example Companies
Satellite manufacturing	Northrop Grumman, Lockheed Martin, Boeing, SSL
Launch vehicle subsystem manufacturers	Aerojet Rocketdyne
Launch service providers	Arianespace, SpaceX, ULA, Northrop Grumman, Blue Origin
Telecommunication	Iridium, Intelsat, Eutelsat, DirectTV, Sirius XM
Earth observation	Planet, Digital Globe
Vehicle tracking	ORBCOMM, Spire
Space tourism	Virgin Galactic, Blue Origin
Satellite servicing	MDA, Northrop Grumman
Space station logistics	SpaceX, Sierra Nevada, Boeing, Northrop Grumman
Space stations	Axiom, NanoRacks, Bigelow Aerospace
Smallsat manifesting	Spaceflight Industries, NanoRacks
Lunar delivery and space resources	Astrobotic, Moon Express, Planetary Resources

Quantitatively, the commercialization of space is observable in the global space economy. According to the Organization for Economic Co-operation and Development (OECD), the space economy can be described as "the full range of activities and the use of resources that create and provide value and benefits to human beings in the course of exploring, understanding, managing, and utilizing space" [12]. Under this description and according to the Space Foundation in a July 2020 report, the global space economy in 2019 was worth an estimated $423.8 billion with commercial revenues accounting for roughly 79.5% ($336.89 billion) of the total space economy [13]. Between 2009 to 2019, the global space economy increased approximately $162.2 billion with commercial growth primarily fueling the increase every year in the decade [13]–[23]. While Space Foundation reports from 2009 to 2013 only describe the growth of commercial space revenues, reports after 2013 explicitly show that commercial space revenues have consistently remained above 76% of the global space economy every year [2], [13]–[23]. Figure 1 depicts the growth of the global space economy from 2009 to 2019 as well as the growth in commercial space revenues from 2014 to 2019.

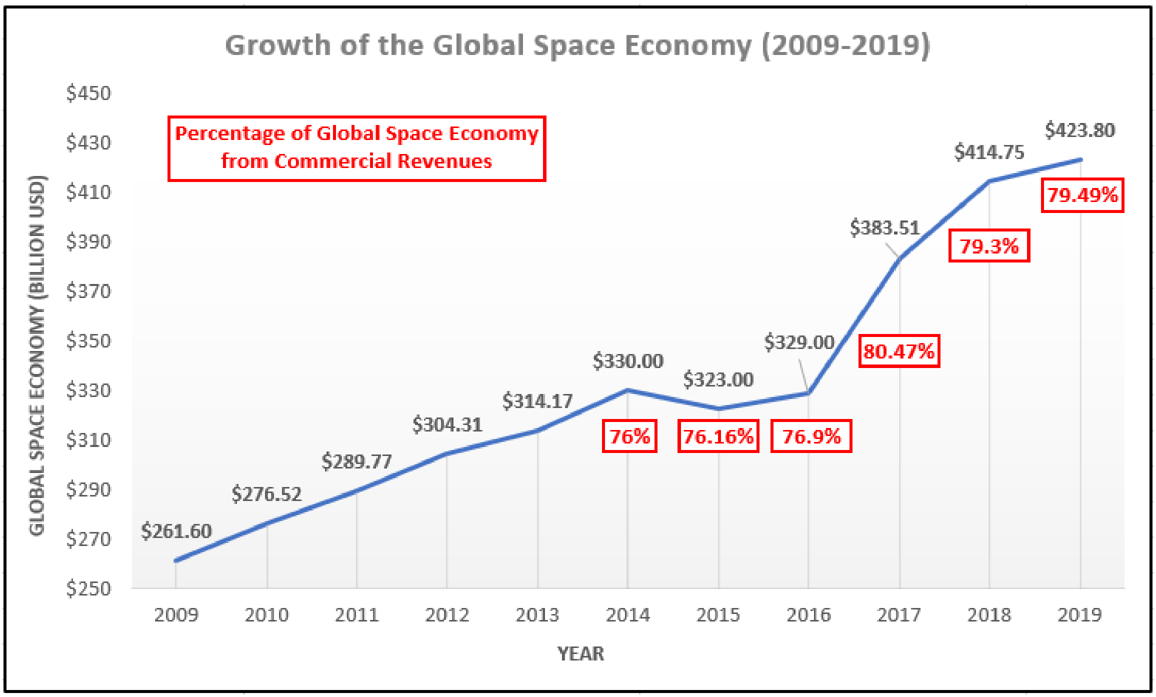

Figure 1. Growth of the Global Space Economy (2009–2019)

While growth in the density and diversity of commercial space entities as well as the growth in the space economy signify the commercialization of space, the trends also suggest that global space activity will only become increasingly dominated by the commercial sector. Within this context, the key challenge moving forward will be maintaining the long-term sustainability and safety of space operations while enabling the continued growth of the commercial space industry.

2. Proliferation of Commercial Satellite Mega-constellations

Satellite constellations are not a new space trend and have been in use for quite some time. Take, for instance, the Global Positioning System (GPS) which became operational in 1993 [24]. The history of GPS can be traced back to the 1950s and 1960s where the U.S. Department of Defense (DOD) launched several "Transit" and "Timation" satellites [25] to track its submarines carrying nuclear missiles [24]. Today, satellite constellations in LEO and in geosynchronous Earth orbit (GEO) provide a variety of space-based capabilities such as communications, navigation, remote sensing, and scientific research. Large commercial satellite constellations, on the other hand, are the most recent trend in space, particularly in LEO, and are becoming more widely desired by commercial actors [2]. Colloquially nicknamed satellite "mega-constellations" [26], large commercial satellite constellations are described as "radically new space architectures" as they can consist of hundreds or even thousands of satellites [11].

While the increase in its popularity primarily stems from several commercial interests like communications and remote sensing [27], the most prominent driver is providing global internet access. In 2019, the International Telecommunication Union (ITU) reported that while 86.6% of individuals in developed countries use the internet, the number drops to 47% in developing countries and drops even further to 19.1% in the least developed countries [28]. Even within the United States, the Federal Communications Commission (FCC) reported in their most recent Broadband Progress Report that 10% of all Americans (34 million), 39% of rural Americans (23.4 million), and 4% of urban Americans lack access to the FCC's threshold for internet access [29]. As such, satellite-provided internet, via mega-constellations, "aims to close the gap by reaching these remote areas, where ground-based infrastructure is either nonexistent or insufficient to provide broadband speeds" [30].

However, to accomplish this task, hundreds to thousands of LEO satellites are required to achieve global and redundant coverage [30]. Coincidentally, the same factors that enabled the commercialization of space have also enabled the proliferation of commercial satellite mega-constellations. As described in a 2018 report by Swiss Re, the world's second largest reinsurance company and, at the time, an insurer of satellites and launches [31], "advances in technology and spacecraft manufacturing have enabled the proliferation of smaller and less expensive but fully capable satellites" [9]. As a result, commercial space entities are now pursuing [9] these "proliferated constellations made up of dozens, hundreds, or even thousands of satellites in low orbits" [11] to provide "almost fiber-optic internet speeds" [30].

For example, SpaceX has not only developed lower costing launch vehicles, but has also deployed its Starlink constellation to provide broadband internet services from LEO [2]. Competitors like Amazon and OneWeb have shown similar ambitions and have together already applied for the operation of thousands of satellites [30]. According to NAPA, "by 2025, as many as 1,100 satellites could be launched per year, quickly eclipsing the approximately 2,800 active satellites that are currently in orbit" [2]. With the satellite internet market alone projected to reach $412 billion by 2040 [32], the number of satellite mega-constellations to soon exist in LEO is concerning. Within this context, the key challenge will be effectively and safely managing thousands of active satellites in a congested low-Earth environment.

3. Growth of Orbital Debris in LEO

As stated in NAPA's August 2020 report, "by all accounts, there is a crisis in space" [2]. In the last half a century of man's space exploration and exploitation activities, the number of space debris in Earth orbit has increased significantly. According to the Inter-Agency Space Debris Coordination Committee, space debris, also known as orbital debris, is defined as "all manmade objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are nonfunctional" [33]. Orbital debris consists of objects like spent rocket bodies, non-operational spacecraft, mission-related objects (rings, bolts, etc.), and fragments generated by collisions or explosions [8], [34]. As of May 2020, the National Aeronautics and Space Administration (NASA) estimates that there are over 100.5 million pieces of orbital debris in LEO [35]. Figure 2 depicts the growth of catalogued objects in Earth orbit from 1956 to 2020 with roughly two-thirds of the objects orbiting in LEO [30].

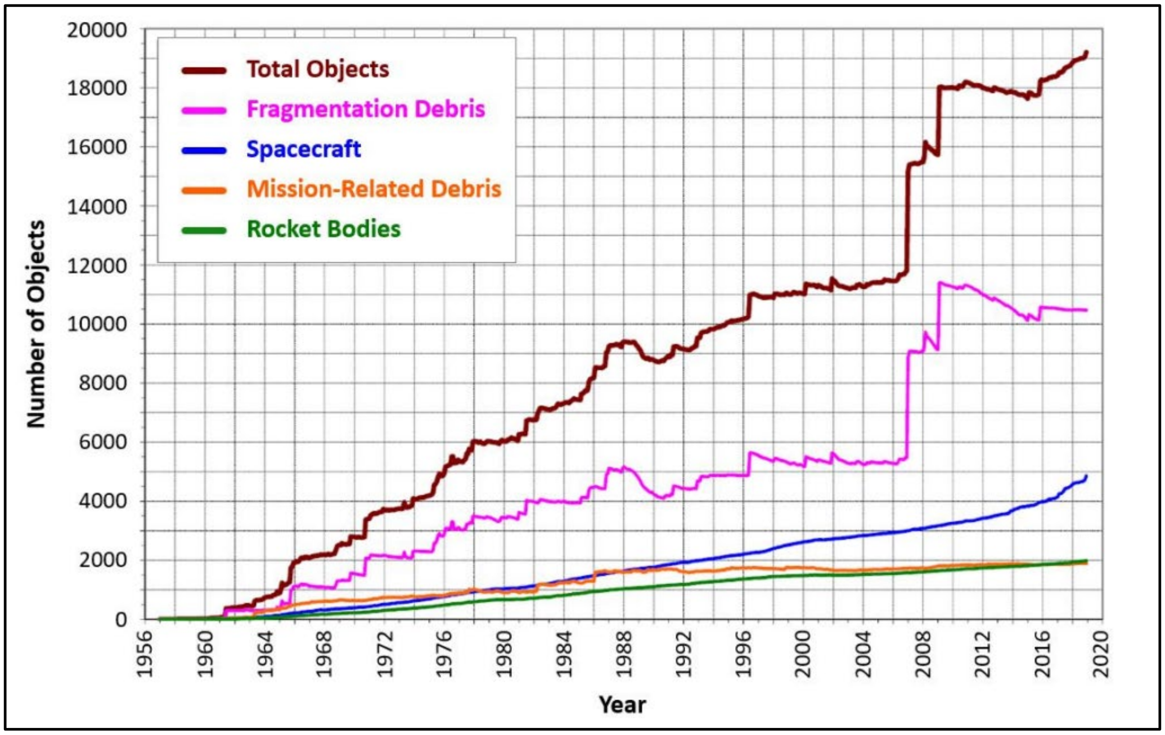

Figure 2. History of Cataloged Objects in Earth Orbit. Source: [30].

While several sources of orbital debris exist, the largest and quickest contributors are intentional breakups and collisions [30]. Intentional breakups are typically associated with anti-satellite (ASAT) weapon tests such as China's ASAT test on a non-operational Chinese weather satellite, the Fengyun-1C (FY-1C), in January 2007 [36]. Sparking international uproar for its contribution of orbital debris in LEO [30], China's destruction of its FY-1C generated a cloud of more than 3,000 pieces of orbital debris which was not only the largest ever tracked [36], but also amounted to one-sixth of all radar-trackable debris [30]. Much of the debris cloud generated by China's ASAT test will remain in orbit for decades and thus poses a significant threat to all current and future spacecraft operating in LEO [36]. Figure 3 provides an illustration of the debris cloud generated by China's

2007 ASAT test. According to NASA's Orbital Debris Program Office in July 2018, "breakup debris have surpassed half of the cataloged Earth satellite population" [37].

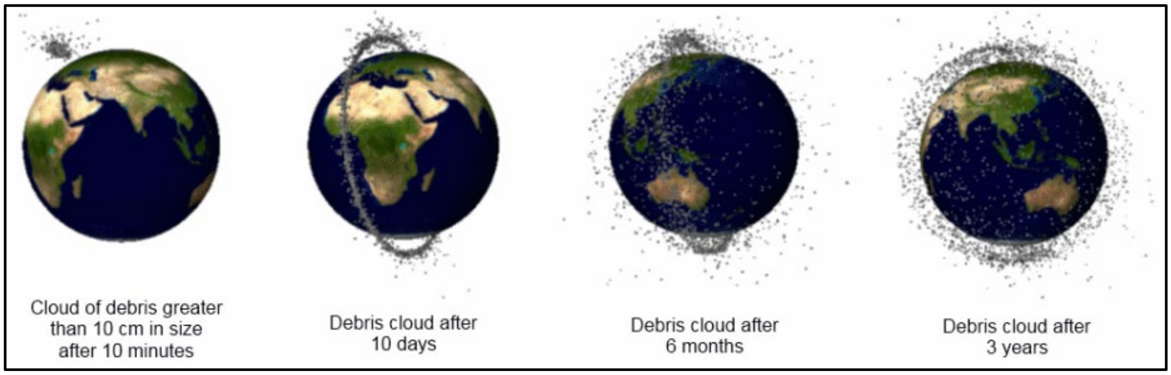

Figure 3. Evolution of the Debris Cloud from 2007 Chinese ASAT Test
Source: [36].

Collisions, on the other hand, are typically unintentional and can occur between two satellites, between two pieces of orbital debris, or between a satellite and a piece of orbital debris. For example, the first collision between two satellites occurred in February 2009 where an active U.S. satellite, Iridium 33, collided with an inactive Russian satellite, Cosmos 2251 [38]. The collision generated nearly 2,000 pieces of orbital debris sized at least 10 cm in diameter with thousands more smaller pieces [38]. Like China's 2007 ASAT test, the debris cloud generated by the Iridium-Cosmos collision will remain in orbit for decades or longer and poses a significant threat to all current and future spacecraft operating in LEO [38]. Figure 4 provides an illustration of the Iridium-Cosmos collision and the resulting debris cloud. Furthermore, a 2019 study for the first International Orbital Debris Conference (IOC) reported that research now suggests the "number density of debris in some LEO altitude regimes have already passed a tipping point where the rate at which new debris added by collisions exceeds the rate at which debris decays" [39]. Though rare, events like intentional breakups and collisions have directly and largely contributed to the debris crisis in LEO [30].

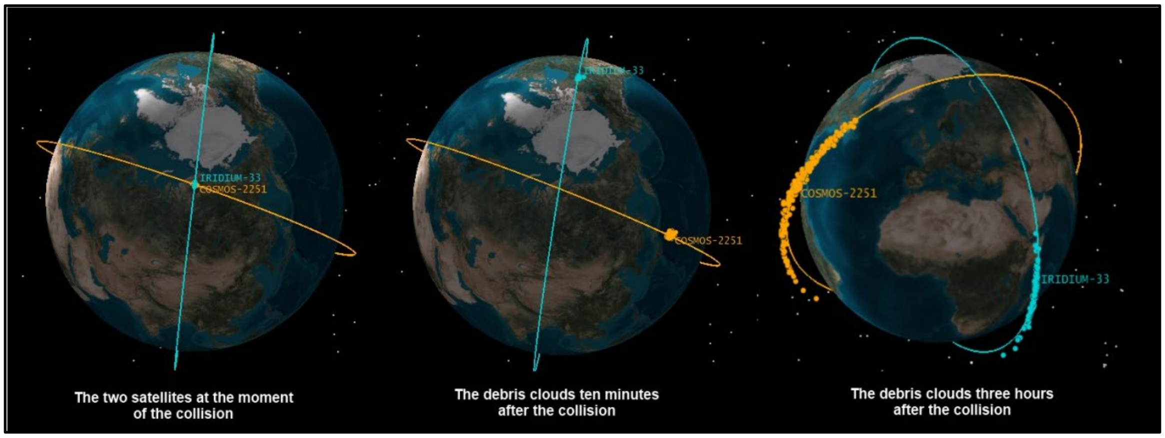

Figure 4. Evolution of the Debris Clouds over First Three Hours from 2009 Iridium-Cosmos Collision. Source: [38].

Today, LEO is "the most debris-filled region" [7] where the number of orbital debris, roughly 100.5 million [35], greatly eclipses the number of active satellites, approximately 1,900 as of September 2020 [7]. The growth of orbital debris, regardless of whether generated by intentional breakups, collisions, explosions, or lack of post-mission disposal, has accumulated to the point where, even with no new launches, collisions among existing objects in LEO will occur over the next 200 years [8]. Within this context, the key challenge will be preventing the generation of new and more orbital debris which already threatens current space safety.

C. PROBLEM STATEMENT

Compounding the risks associated with satellite and orbital debris congestion in LEO is the growing utilization of commercial satellite mega-constellations. Although these large space architectures undoubtedly provide enhanced capabilities and services, the sheer number of satellites involved with these architectures poses a significant risk in the low Earth space operating environment. If left inappropriately managed, commercial satellite mega-constellations could become a significant source of debris themselves [9]. As the surge of commercial satellites in LEO continues, the management of commercial satellites, which currently do not address large constellations appropriately, must improve to ensure the long-term sustainability and safety of space operations while also enabling growth of the space industry.

As such, this thesis aims to address **how to improve the management of commercial satellite mega-constellations to ensure the sustainability and safety of LEO as well as enable growth of the commercial space industry**. Although "management" is a relatively broad term, this thesis divides the concept into three areas for examination: pre-launch, on-orbit, and post-mission. Furthermore, due to the significant lack of documents, verbiage, and rules that specifically apply to commercial satellite mega-constellations, this thesis examines the "management" of these large space architectures through the management of commercial satellites in general. Each of the following three chapters, in respect to its segment of management, describes significant entities and their roles, pertinent documents and their functions, and areas of concern raised by commercial satellite mega-constellations. The fifth chapter addresses these concerns and offers recommendations for improving the management framework of commercial satellite mega-constellations.

D. LITERATURE REVIEW

While examination of the U.S. management of commercial satellites and mega-constellations will come in the following chapters, it is critical and necessary to first examine the means of space governance in which future improvements should derive. For instance, space governance can take form as a single entity (where improvements leverage authoritative power) or several entities (where improvements leverage communal responsibility), and can be exercised through soft (guidelines, standards, best practices) or hard governance (laws and regulations). These factors can ultimately indicate whether improvements to the U.S. management framework for commercial satellites and mega-constellations are feasible or even necessary. While so, space is inherently an international domain. Thus, it would be naïve to assume that any improvements made to U.S. management framework will transcend into the international domain if not appropriately framed and enabled to do so. As such, rather than focusing on an approach specifically tailored to the United States, the following section explores an approach tailored to the international community which can then be initiated by the United States at the national level.

First, it is important to examine the overarching international space governance framework upon which national space governances derive and reference. In *Crowded Orbits: Conflicts and Cooperation in Space*, Dr. Clay Moltz analyzes three potential international space governance frameworks: (1) "military hegemony based on relative power," (2) "piecemeal global engagement based on consensual norms," and (3) "enhanced international institutions based on new treaties and legal mechanisms" [40]. Within the first framework, a space hegemony establishes dominance within the space domain and thereby exercises space governance through the employment of military force to "maintain effective control of space in a way that is perceived as tough, nonarbitrary, and efficient" [40]. However, this framework is not only unrealistic, but is also, as Moltz argues, "unlikely to lead to beneficial and sustainable outcomes" [40].

Within the second framework, the international community exercises space governance by pressuring space actors to conform to consensual norms [40]. As Moltz describes, the second framework is much like today's form of space governance that muddles through "limited, piecemeal treaties and ad hoc problem solving" which, as Moltz claims, "has arguably worked so far and could conceivably be extended into the future" [40]. However, this framework, which is the current means of space governance, progressively proves to be inadequate. For more than a decade, international discussions regarding space security have ranged from proposals for new international space organizations and treaties to codes of conduct and "purely voluntary means of self-restraint" [40]. Ultimately, there is significant difficulty for spacefaring nations to reach consensus especially "in a field where there is a great deal of dual-use technology, enduring military distrust among leading actors, and questions about the viability of future agreements in terms of compliance and verification" [40]. As such, today's means of space governance, an international forum of sorts, is insufficient at addressing growing space activities and lacks the formal mechanisms required to enforce established rules.

In Moltz's third and final framework, enhanced and international institutions that possess technical competence and a commitment to "optimize current and planned space activities with the goal of sustaining the environment" exercise space governance [40]. Within this framework, international entities that represent "all nations conducting space activities" exercise space governance through formal negotiations, legally binding agreements, and political influence [40]. As Moltz proposes, such a regime would look similar to the governance structure of the International Space Station (ISS) which "is not an ad hoc norm-based mechanism, but instead a formal organization based on intergovernmental agreements that specify a complex formula of contributions and access for each country" [40]. The success of the ISS, which stems from "the clarity of its rules and the fact that it is a limited self-interested body not dependent on the United Nations or large numbers of non-spacefaring nations" [40], offers a framework which seemingly possesses the best chance of transcending to international space governance for commercial satellite mega-constellations.

However, progress in international space governance has been particularly slow since the mid-1970s [40], and thus a proposal of such an enhanced international institution seems like a tremendous leap forward from today's means of space governance. While an end-state to space governance may be relatively clear, the starting point for efforts to concentrate is less clear. Nevertheless, some direction can be drawn from commonly shared opinions within the commercial space industry. In *Space Governance in the New Space Era*, Daniel L. Oltrogge and Ian A. Christensen state that the space industry is "generally not keen to be regulated because regulations can impose inconveniences, constraints, delays and costs" [41]. This is more applicable for experienced satellite operators who, after decades of involvement in satellite activities, are cognizant of "what works best for their operations" and "have developed long-standing procedures, best practices and norms of behavior" [41]. For these reasons, the authors state that "non-binding voluntary industry best practices and self-governance tend to be favored by space operators and [the] commercial industry" [41]. To this end, perhaps the establishment of a new international entity that prescribes "non-binding voluntary industry best practices" [41] may be an acceptable place to begin concentrating efforts.

In *A Practical Perspective on Space Traffic Management*, Dr. Darren McKnight proposes the establishment of a "public-private partnership" called the Space Operations

Assurance Consortium (SOAC) [42]. Although specifically focused on space traffic management, the SOAC is an example of an enhanced international institution, described by Moltz, that could conceivably prescribe "non-binding voluntary industry best practices" [41], described by Oltrogge and Christensen. As explained by McKnight, the SOAC would ultimately "facilitate deliberate interactions between stakeholders" regarding Space Operations Assurance (SOA) activities [42]. McKnight states that the SOAC would not only help develop and define the three components (i.e., space situational awareness, space traffic management, and space environment management) of the SOA framework, but would also "help manage interactions and results from and across these three domains" [42] which can notionally include prescription of "non-binding voluntary industry best practices" [41].

However, any concept involving an international entity prescribing standards, best practices, or norms, regardless of whether they are binding or non-binding, is subject to one significant challenge which is buy-in. As discussed by Moltz, spacefaring nations have historically proved to be ineffective at reaching consensus for space activities [40]. Achieving buy-ins for voluntary standards, best practices, or norms from spacefaring nations is no different of a case. In the example of McKnight's SOAC, however, McKnight suggests that the SOAC "be established at a national level and then combined into bilateral and multilateral implementations before trying to execute globally" [42]. If applied to the management of commercial satellite mega-constellations, this approach could offer great potential. However, such a national level entity must first be effective before being combined into "bilateral and multilateral implementations" [42]. What remains unclear is whether or not the designated national-level entity requests or mandates compliance to standards, best practices, and norms.

Regardless of how the SOAC-like national entity comes about, the designated entity must consider the appropriate approach to managing its satellites, including commercial satellite mega-constellations, at the national level. Two basic types of space governance can be employed: binding and non-binding space governance [41]. Binding space governance, considered "hard" governance, utilizes legally binding agreements or normative instruments like national standards and regulations [41]. Non-binding space governance, considered "soft" governance, utilizes voluntary or non-normative agreements [41]. Although space entities seem to prefer non-binding or soft space governance, binding or hard space governance provides legal or regulative authority to management entities for enforcing rules and mitigating undesired or dangerous activities in space. To effectively manage commercial satellite mega-constellations, the consideration of whether to employ soft or hard space governance is critical in ensuring that efforts are appropriate and not potential backsteps.

As discussed in the work of Oltrogge and Christensen, the space industry is generally in favor of less regulation [41]. As such, Dr. Michael P. Gleason in *Establishing Space Traffic Management Standards, Guidelines and Best Practices* strongly emphasizes the application soft law in space governance [43]. While Gleason notes the need and lack of hard space regulations, he suggests that the first step in "protecting the space environment is for commercial actors, in collaboration with government and international stakeholders, to develop internationally accepted, voluntary standards, guidelines, and best practices" [43]. Similarly, in *A Path Forward to Better Space Security: Finding New Solutions to Space Debris, Space Situational Awareness and Space Traffic Management*, Dr. Joseph N. Pelton suggests that nations consider adopting a series of soft law initiatives to deal with current space security issues [44]. Pelton's suggestion offers great potential due to the better likelihood of space entities galvanizing industry-wide cooperation and support to address pertinent space security issues.

Although it is now seemingly apparent that soft space governance is the preferred way forward, it is by no means the final solution. The presented works above merely highlight the first appropriate step in bringing space entities together via soft space governance. Finer details that comprise governance such as entities, documents, and processes now require examination to determine if soft governance is practically appropriate for addressing concerns raised by commercial satellite mega-constellations.

II. PRE-LAUNCH MANAGEMENT

A. INTRODUCTION

The pre-launch management of commercial satellites ensures the proper preparation and safety of satellites for launch and operations once on-orbit. Activities include reviewing and assessing satellite compliance with both national and international requirements as well as approving satellite launch and on-orbit activities. At the international level, numerous entities and documents provide guidance for pre-launch management activities. However, the list narrows when only considering those that mandate compliance from U.S. commercial satellites. The United Nation's (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) and the ITU's Radiocommunication Sector (ITU-R) are the only international entities that mandate compliance. The UN's "Outer Space Treaty" (OST) and "Registration Convention" (REG) as well as the ITU's Radio Regulations (RR) are the only international documents that mandate compliance. The rules established by these international management mechanisms are implemented at the U.S. national level by three federal entities—the Office of Space Transportation (AST), the Satellite Division, and the Commercial Remote Sensing Regulatory Affairs Office (CRSRA). All three federal entities possess regulatory authority [3] and thus apply and regulations and policies to U.S. commercial satellites in addition to implementing requirements established by international treaties, agreements, and principles. Generally satisfying the international obligations of the United States [45], current U.S. pre-launch management processes focus on three areas of satellite operations: launch, communications, and remote sensing. This chapter identifies and describes key entities, pertinent documents, current processes, and significant areas of concern within the U.S. pre-launch management architecture.

B. SIGNIFICANT ENTITIES

At the international level, several entities are involved in the pre-launch management of U.S. commercial satellite mega-constellations to varying degrees. Among these entities, only COPUOS and the ITU-R possess the authority to prescribe national-level requirements and thereby mandate compliance from U.S. commercial satellites. Although COPUOS and the ITU-R primarily operate through binding requirements, two other international entities contribute to the pre-launch management of U.S. commercial satellite mega-constellations through non-binding guidelines and best practices—the Inter-Agency Space Debris Coordination Committee (IADC) and the Space Safety Coalition (SSC). At the national level within the United States, the AST, Satellite Division, and the CRSRA collectively conduct the pre-launch management of commercial satellites in which they oversee, regulate, and facilitate activities and requirements for their respective areas of expertise.

1. International Entities

- **COPUOS**, established in 1959, is a permanent committee within the UN that governs the global "exploration and use of space for the benefit of all humanity" [46]. COPUOS reviews international cooperation in space activities, studies space-related legal issues [46], and facilitates forum-like discussions for governments to address matters pertaining to international space governance [2]. Although COPUOS does not actively manage satellite activities, the discussions and resulting resolutions of COPUOS have established a broad international framework that outlines appropriate behaviors and activities in space. As such, COPUOS establishes the requirement for spacefaring nations, those opting to comply, to be responsible for supervising and approving all respective governmental and non-governmental space activities [47]. Additionally, COPUOS establishes the requirement for those spacefaring nations to maintain a registry of all objects launched into space as well as submitting objects to the UN Secretary General [48]. As of 2019, COPUOS has 95 member states [49].

- The **ITU-R**, established in 1927 as the International Radio Consultative Committee then renamed in 1992 [50], is a sector of the ITU that ensures the "rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services" including those that utilize satellite orbits [51]. The ITU-R maintains the Master International Frequency Register (MIFR) which "records the international rights and obligations of satellites and associated Earth stations" to utilize the radio frequency (RF) spectrum [52]. Additionally, the ITU-R maintains the RR and implements the rules and intents therein to ensure "interference free operations of radiocommunications systems" [53]. In regard to the pre-launch management segment, the ITU-R manages, allocates, and assigns portions of the RF spectrum for satellites [54].

- The **IADC**, established in 1993 [55], is an "international governmental forum for the worldwide coordination of activities related to the issues of man-made and natural debris in space" [56]. As an international consortium of national space agencies [2], the IADC facilitates information exchange and fosters international cooperation in orbital debris research, space activities, and the development of debris mitigation responses and techniques [2], [56]. In addition, the IADC is a critical informer of space debris mitigation for the international community [57]. Although the IADC does not prescribe international nor national requirements for the pre-launch management segment, it maintains and offers a voluntary collection of advisable satellite design considerations and operational concepts known as the IADC Space Debris Mitigation Guidelines. As of April 2021, the IADC has 13 national space agencies [56].

- The **SSC**, recently established in 2019, is an "ad hoc coalition of companies, organizations, and other government and industry stakeholders that actively promotes responsible space safety" [58]. The SSC adopts and improves on "international standards, guidelines, and practices" relevant to space safety [58]. Like the IADC, the SSC does not prescribe international nor national requirements for the pre-launch management of commercial satellites. However, the SSC maintains and offers a voluntary collection of advisable satellite design considerations and operational concepts known as the Best Practices for the Sustainability of Space Operations. As of April 2021, the SSC has 48 commercial endorsees [59] and currently leads in the development of best practices that sustain the space operating environment [2].

2. U.S. National Entities

- The **AST**, established in 1984, is an office within the Federal Aviation Administration (FAA) at the Department of Transportation (DOT) that regulates "the U.S. commercial space transportation industry to ensure compliance with international obligations of the United States" [60]. Delegated to execute the DOT's responsibility of managing and facilitating U.S. commercial launch operations [61], the AST permits and licenses launches, spaceports, and transportation vehicles [2], [62]. As the "FAA's only space-related line of business" [60], the AST implements the rules and intents established in Chapter III within Title 14 of the Code of Federal Regulations (14 CFR) on commercial satellites along with any international requirements.

- The **Satellite Division** is an office within the International Bureau at the FCC that licenses the use of the RF spectrum by commercial U.S. satellites [62]. Delegated to execute the FCC's responsibility for regulating the domestic and non-federal use of the RF spectrum by satellites [57], [62], the Satellite Division implements the rules and intents established in Chapter I within Code of Federal Regulations (CFR) Title 47 (47 CFR) to regulate commercial satellite communications [62], [63] and to foster the "efficient use of the radio frequency spectrum" [63].

- The **CRSRA** is an office within the National Oceanic and Atmospheric Administration (NOAA) at the Department of Commerce (DOC) that licenses U.S. commercial space-based remote sensing systems and operations [64]. Delegated to execute the DOC's responsibility of licensing "private sector parties to operate private remote sensing space systems" [65], the CRSRA implements the rules and intents established in Chapter IX within 15 CFR and addresses remote sensing concerns regarding national security, foreign policy, and international compliance [62].

- The **Office of Space Affairs** is an element within the Bureau of Oceans and International Environmental and Scientific Affairs (OES/SA) at the Department of State (DOS) [66] that primarily "handles international space issues and represents the United States in [COPUOS]" [2]. Although most of the Office's activities pertain to outward-facing civil and international space matters [2], it maintains the "official U.S. registry of objects launched into outer space" [66], an OST requirement established within the OST.

C. PERTINENT DOCUMENTS

At the international level, numerous documents are involved in the pre-launch management of U.S. commercial satellite mega-constellations. Among these documents, the OST, REG, and RR are binding for U.S. commercial satellites. In addition, few non-binding documents contribute to the pre-launch management of U.S. commercial satellite mega-constellations—COPUOS' Long-Term Sustainability Guidelines (LTS Guidelines), Space Debris Mitigation Guidelines of COPUOS, the IADC Space Debris Mitigation Guidelines, and the SSC's Best Practices for the Sustainability of Space Operations. In the United States, numerous national documents support the pre-launch management of commercial satellites by sanctioning regulatory authority for federal entities, outlining regulative requirements, and advising satellite conditions and concepts.

1. International Treaties, Agreements, and Principles

- The **OST**, officially known as the Treaty of Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, is a treaty maintained by COPUOS that "provides the basic framework on international space law" [47]. Effective since October 1967 [47], the OST outlines broad principles for appropriate behaviors and activities in space to promote international cooperation on peaceful space activities. The OST is binding for nations that have ratified the agreement and is therefore binding for U.S. commercial satellites [67], [68]. Although numerous articles exist within the OST, pertinent to the pre-launch management of commercial satellites is Article VI in which the COPUOS establishes signatories as responsible for the authorization and supervision of all respective governmental and non-governmental space activities [69]. As of January 1st, 2020, 110 countries have ratified the treaty [68].

- The **REG**, officially known as the Convention on Registration of Objects Launched into Outer Space, is also a treaty maintained by COPUOS and provides a framework in which there is "a means to assist in the identification of space objects" [70]. Effective since September 1976 [70], the REG empowers the UN Secretary General to "maintain a registry of objects launched into space" [2] and to "ensure full and open access to the information" [70] for all interested parties. Like the OST, the REG is binding for nations that have ratified the agreement and is therefore binding for U.S. commercial satellites [67]. Within the document Article II mandates signatories to maintain a registry of all objects launched into space in addition to submitting objects to the UN Secretary General [48]. As of January 1st, 2020, 69 countries have ratified the agreement [68].

- The **LTS Guidelines**, officially known as the Guidelines for the Long-Term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space [71], is a "set of 21 voluntary consensus Guidelines" that promote and ensure the long-term sustainability of space activities [72]. Effective since June 2019 [71], the LTS Guidelines is "intended to support the development of national and international practices and safety frameworks for conducting outer space activities" as well as the mitigation of associated risks [72]. While the document provides advisable practices in all three segments of satellite management, pertinent to the pre-launch segment is Guideline A in which COPUOS provides best practices for the supervision of national space activities and enhancement of registering space objects, among others [72].

- The **RR** is an ITU-generated rulebook that "contains the complete texts of the Radio Regulations adopted by the World Radiocommunication Conference of 1995" [73]. The RR is "binding under a 1992 treaty, the Constitution and Convention of the International Telecommunications Union" [62] and is therefore binding for U.S. commercial satellites. The RR supports the ITU-R in facilitating "the efficient and effective operation of all radiocommunication services" [74] including satellite communications.

- The **IADC Space Debris Mitigation Guidelines** describes "existing practices that have been identified and evaluated for limiting the generation of space debris in the environment" [33]. As the first set of "documents in the international sphere [that] accumulated the space debris mitigation practices of space agencies" [75], the IADC Space Debris Mitigation Guidelines offers a voluntary collection of mitigation measures that limit orbital debris in all three segments of satellite management. Specific to the pre-launch management segment, however, Mitigation Measures 5.1 and 5.2 provide satellite design considerations and operational concepts that mitigate orbital debris.

- The **Space Debris Mitigation Guidelines of COPUOS** is based on the elements of the IADC Space Debris Mitigation Guidelines [75]. Effective since December 2007, the document, like the source it is based on, provides broad guidelines that mitigate orbital debris in the "mission planning, design, manufacture and operational (launch, mission, and disposal) phases" of satellites [76]. Pertinent to the pre-launch management of commercial satellites are Guidelines 1 to 3 in which COPUOS provides satellite design considerations and operational concepts that mitigate the generation of orbital debris.

- The **Best Practices for the Sustainability of Space Operations** is an SSC-generated document that addresses "gaps in current space governance and [promotes] better spacecraft design, operations and disposal practices aligned with long term space operations sustainability" [58]. Released in September 2019 [77], the Best Practices for the Sustainability of Space Operations was developed and is updated collectively by numerous commercial space companies to provide consensus-based standard practices for responsible and safe space activities in all phases of satellite operations [58]. Unlike most of the previously discussed international documents, the SSC-generated document provides more detailed and study-based design considerations and operational concepts for both satellites and constellations. Relevant to the pre-launch management of commercial satellites, Best Practices 3 to 4 provide guidance for safer satellite and constellation designs.

2. National Laws, Regulations, and Policy Directives

- The **United States Government Orbital Debris Mitigation Standard Practices (USGODMSP)**, is a national-level guideline that provides key objectives and core standard practices for limiting and minimizing orbital debris resulting from space activities. Initially developed in 2001 [78], [79], the USGODMSP "establishes a framework for debris mitigation requirements" and mandates compliance from USG agencies and organizations while allowing those entities to "impose more specific or more stringent rules" [80]. The USGODMSP provides a collection of advisable designs and operational concepts for satellites and constellations which are implemented through the licensing processes of the AST, Satellite Division, and CRSRA [62].

- The **Commercial Space Launch Act of 1984**, effective since October 1984, is a "federal law authored to facilitate the private enterprise of the commercialization of space and space technology" [81]. In recognition of the private sector as a legitimate and viable option for outsourcing government launching facilities and services [81], the Act stands as the "legal basis for commercial space launch policy" [82]. Furthermore, the Act tasks the DOT to oversee and coordinate commercial launches as well as the issuing of licenses and permits for commercial launches and reentries [81].

- **Title 14 of the Code of Federal Regulations (14 CFR), Chapter III** contains the FAA's regulations on commercial space transportation activities that satisfies compliance and authorization mandates outlined in the OST and Commercial Space Launch Act of 1984. Titled *Commercial Space Transportation, Federal Aviation Administration, Department of Transportation* [83], Chapter III of 14 CFR promulgates the requirement for commercial space companies to obtain a license for launch and reentry operations from the FAA.

- **The Communications Act of 1934**, built upon the Radio Act of 1927, established the FCC to stabilize and regulate both interstate and foreign communications by radio, television, and wire during a period in which the radio industry was rapidly growing [84]. Later amended to include the regulation of satellite telecommunications [2], the Communications Act of 1934 currently remains as the FCC's source of broad regulatory authority to license the RF use of commercial satellite communications and to implement requirements established by the ITU-R [62].

- **47 CFR, Chapter I**, titled *Federal Communications Commission* [85], contains the FCC's regulations on all telecommunications activities and satisfies authorization and oversight mandates outlined by the ITU Radio Regulations. Chapter I of 47 CFR promulgates the requirement for commercial space companies to obtain a license for their satellites to utilize the RF spectrum.
- Although the **Land Remote-Sensing Policy Act of 1992** repealed the **Land Remote-Sensing Commercialization Act of 1984** [65], both acts were critical in empowering the DOC to "license and regulate the private remote-sensing industry" [2]. The Land Remote-Sensing Policy Act of 1992 currently remains as the CRSRA's source of regulatory authority to license commercial remote sensing space systems.
- **15 CFR, Chapter IX, Part 960**, titled *Licensing of Private Remote Sensing Space Systems* [86], contains NOAA's regulations on commercial remote sensing activities that satisfies authorization and oversight mandates outlined in The Remote Sensing Principles and the Land Remote-Sensing Policy Act of 1992. 15 CFR Chapter IX Part 960 promulgates the requirement for commercial space companies to obtain a license for space-based remote sensing operations from NOAA.
- **Space Policy Directive – 2, Streamlining Regulations on Commercial Use of Space (SPD-2)**, issued in May 2018, calls on federal space entities involved in the pre-launch management of commercial satellites (i.e., DOT, DOC, FCC), among others, to "review existing regulations and ensure rules are not duplicative while also promoting economic growth, advancing national security and foreign policy goals" [87]. As a result of the considerations and intents presented in the directive, several federal entities involved with commercial space activities have updated their policies and rules. Examples include the FAA/DOT amending 14 CFR to "consolidate multiple regulatory parts to create a single licensing regime

for all types of commercial space flight launch and reentry operations" [88], the FCC amending 47 CFR to "streamline the licensing process for small satellites" [57], and NOAA/DOC amending 15 CFR to "streamline the licensing process for U.S. satellite remote sensing operators" [89].

D. KEY PROCESSES

Before U.S. commercial satellites launch and integrate with their mega-constellations in LEO, licensing procedures and regulative requirements properly prepare the satellites for launch and operations once on-orbit. Current U.S. pre-launch management processes include reviewing and assessing satellite compliance with both national and international requirements as well as authorizing satellite launch and on-orbit activities. Although U.S. pre-launch management processes have primarily focused on regulating and authorizing satellite launch, communications, and remote sensing activities, they now also focus on orbital debris mitigation.

1. Radio Frequency License Requirement

All satellites require use of the RF spectrum to communicate with either terrestrial stations or another spacecraft. The RF spectrum, however, is finite and thus requires coordination and synchronization in its usage to prevent or mitigate interference [2]. As a result, commercial space companies that intend to operate satellites that utilize RF must obtain a license from the FCC to use a portion of the RF spectrum, as mandated by the Communications Act of 1934 [62]. Alongside licensing RF use for satellites, the FCC also implements international requirements established by the ITU's RR [62]. Currently, the Satellite Division within the FCC's International Bureau licenses the majority of U.S. commercial satellites under the regulatory procedures outlined in Part 25, *Satellite Communication*, of 47 CFR [62]. Through the FCC, the United States applies the ITU's Radio Regulations, which are binding under a 1992 treaty known as the Constitution and Convention of the ITU [62], to all commercial satellites that utilize the RF spectrum [2].

2. Remote Sensing License Requirement

Mandated by the Land Remote Sensing Policy Act of 1992, commercial space companies that intend to operate remote sensing satellites must obtain a license from the CRSRA to do so [65]. In the process of issuing licenses, the CRSRA is "required by law to consult with 'other appropriate United States Government agencies' to ensure that any national security or foreign policy concerns are addressed and to ensure compliance with international obligations" [62]. According to an April 2017 memorandum of understanding, the principal entities that must be consulted are the DOC, DOS, DOD, and Department of the Interior (DOI) [90]. Currently, the CRSRA licenses remote sensing missions for individual satellites or for entire satellite constellations [62].

3. Launch License Requirement

As mandated by the Commercial Space Launch Act of 1984, any entity intending to launch and/or operate a launch vehicle or site within the United States must obtain a license to do so [91]. As a result, commercial space companies planning to launch a satellite into orbit must obtain a license from the FAA's AST for the operation of commercial launch vehicles [62]. Currently, the AST provides two types of licenses: specific and operator licenses. The specific license "authorizes one or more individually identified launches, all at the same site and using the same type of vehicle" [62]. The operator license "authorizes an unspecified number of launches, using a family of similar but not necessarily identical vehicles, over a period of years" [62]. In addition, spaceports, which are commercial launch and reentry sites, must be licensed to conduct activities [62]. As of January 2021, 12 spaceports have active spaceport operator licenses [62].

4. Third-Party Liability Insurance Requirement

Once a launch license is issued, the AST further requires launch providers to obtain liability insurance as required by Chapter III of 14 CFR [83]. The required insurance amount is based on "the maximum probable loss from claims by (a) a third party for death, bodily injury, or property damage or loss resulting from an activity carried out under the license; and (b) the United States Government against a person for damage or loss to Government property resulting from an activity carried out under the license" [92].

Although the statutory cap is currently set at $500 million, the federal government, in the event of a loss greater than the initially required insurance amount, can compensate licensees up to an additional $3.1 billion [62].

5. Orbital Debris Mitigation Plan Requirement

As a result of the USGODMSP requiring all "federal agencies that acquire or operate spacecraft" to apply the document's principles to their processes [62], the AST, FCC, and CRSRA require commercial satellite operators to submit an orbital debris mitigation plan as part of their respective licensing processes [3]. For the AST, Chapter III of 14 CFR requires satellite operators, as part of their license application, to provide an orbital debris mitigation plan that meets (1) specified criteria for the probability of collision for satellite launch and reentry operations and (2) "safety at end of launch" standards [93]. For the FCC, Chapter I of 47 CFR requires satellite operators, as part of their license application, to provide an extensive list of statements and demonstration describing their orbital debris mitigation plan [94]. Lastly for NOAA, Chapter XI, Part 960 of 15 CFR requires satellite operators, as part of their license application, to provide "plans and procedures for end-of-life disposal" [62].

E. AREAS OF CONCERN

The U.S. pre-launch management of commercial satellites ensures the proper preparation and safety of satellites for launch and operations once on orbit. Although current pre-launch management processes review and evaluate commercial satellite compliance to launch, communications, remote sensing, and orbital debris mitigation requirements, these prerequisites for satellite operations may not be sufficient to appropriately confront commercial satellite mega-constellations. As these constellations are expected to usher in large numbers of new satellites in LEO [7], current pre-launch management requirements may need to incorporate minimum thresholds for satellite size, maneuverability, and trackability as the absence of these elements can significantly strain on-orbit management activities and efforts.

1. Absence of Minimum Satellite Size

Currently, no pre-launch management requirements outline a minimum size for commercial satellites. While there has not been a legitimate reason to manage this aspect of satellites, the rising trend in commercial utilization of smaller satellites and larger constellations now calls for some consideration in a minimum size for satellites. Traditionally, satellites have been large and heavy due to the technological constraints of their time. For instance, the Hubble Space Telescope, which launched in April 1990 and remains operational, has a mass of 10,886 kg and is the size of a large school bus [95]. Today, however, small satellites, nicknamed SmallSats [96], are increasingly "displacing school bus-sized satellites" for a variety of space-based services like "communications, broadband internet, remote sensing, and Earth observation missions" [27]. Although SmallSats can be described as a "spacecraft with a mass less than 180 kilograms and about the size of a large kitchen fridge" [96], several categories exist within this description. For instance, there are minisatellites (100 to 180 kg), microsatellites (10 to 100 kg), nanosatellites (1 to 10 kg), picosatellites (0.01 to 1 kg), and femtosatellites (0.001 to 0.01 kg) [96]. Although the nanosatellite category is one of the most popular small satellite categories mainly because of the CubeSat standard design [97], the femtosatellite category is quickly making its debut. Femtosatellites (e.g., chipsats) are cracker-sized satellites that have already deployed to LEO and demonstrated the feasibility and viability of extremely small and inexpensive satellites [98].

However, as satellites become increasingly smaller in size, they inherently become more difficult to detect and thus more difficult to track [57]. This is a significant concern as commercial space entities aim to deploy larger constellations [11]. To illustrate, Cornell University, in November 2018, launched a shoebox-sized satellite into LEO which later deployed 105 chipsats in March 2019 [98]. Although the chipsats, a Cornell University project known as KickSat, burned up in the atmosphere on their return to Earth a few days after deployment, they highlighted a significant issue. The chipsats were mere circuit boards that measured 3.6 cm across [98]. Furthermore, very few space entities are currently able to comprehensively detect and track space objects smaller than 10 cm in LEO. For instance, the DOD, via its Space Surveillance Network (SSN), is primarily capable of tracking objects that are “larger than about 10 centimeters in diameter” [62]. Although the DOD recently declared its new S-band tracking radar (i.e., Space Fence) operational in March 2020 [99], capable of detecting marble-sized objects [100] down to 2–5 cm [101], Space Fence remains as the only radar within the SSN to possess this capability. Similarly, LeoLabs, a premier U.S. commercial space situational awareness company, is primarily capable of tracking objects that are “10 centimeters across and larger” [102]. Although LeoLabs also recently declared two new S-band tracking radars (i.e. Costa Rica Space Radars) operational in April 2021, capable of “detect [ing] objects as small as 2 centimeters” [103], it remains as one of very few commercial entities to possess this capability.

In 2018, the FCC denied an application from Swarm Technologies, a Silicon Valley start-up that makes and operates SmallSats to provide internet access, to launch four CubeSats into LEO on the grounds that the satellites were “too small to be tracked” [27]. While this event can seem to be an example of a “working” mechanism that prohibits extremely small objects from launching into space, the process is inefficient and ultimately damaging to the growth of commercial space. As in the case of Swarm Technologies, resources can undoubtedly waste due to the current pre-launch management process that is not based on an established requirement for minimum satellite size. Furthermore, the process could strain as more new commercial satellite operators apply for the operation of smaller satellites and larger constellations [11]. According to the Congressional Research Service (CRS), regulators and policymakers are already “struggling to keep pace with small satellites” [27]. As such, the absence of a minimum size for satellites is not only a concern for pre-launch management activities, but also for on-orbit management activities.

2. Absence of Minimum Satellite Maneuverability

Pre-launch management requirements do not outline a minimum capability for propulsive maneuvering in commercial satellites. While the matter has been a topic of discussion due to international and national orbital debris considerations, many satellites already deployed or deploying to LEO today do not possess onboard propulsive capability [57]. As discussed, the rising trend in the commercial utilization of satellite mega-constellations is expected to result in "[o]rder-of-magnitude or more increases in satellites" [104]. The increase in the number of satellites inevitably leads to a "higher spatial density and a correspondingly higher collision rate" [39] which threatens the operations of all satellites. Therefore, the current absence of a minimum satellite propulsive capability can significantly complicate on-orbit management efforts, specifically space traffic management, to avoid collisions. Fundamentally, space traffic management can only work if "at least one of the two objects [in a potential collision] is maneuverable" [105]. Within this context, at least "86% of the collisions among cataloged objects cannot be avoided today" [105]. Furthermore, one study reveals that "the rate of collision between an active satellite and debris is substantially higher than the collision rate between two active satellites" in many altitude regimes of LEO [67]. As such, it is imperative to ensure that all future satellites are capable of maneuvering via onboard propulsive capabilities.

3. Absence of Minimum Satellite Trackability

No pre-launch management requirements outline a minimum capability for satellites to possess either active or passive means of cooperative identification and tracking which can aid terrestrial or space-based space awareness. Passive means can include components such as radar and laser reflectors (e.g., corner reflectors or retro-reflectors) whereas active means can include components such as light emitting diodes (LEDs) and GPS or RF transponders [2], [10], [106]. In either case, both passive and active means of cooperative identification and tracking enable improved tracking of satellites. Furthermore, it is important to note that the DOD's capability of monitoring and tracking space objects is rooted in a "legacy architecture that originated in missile warning and in an era where there were few objects in space" [57]. As a result, the DOD's space awareness architecture (i.e., sensor systems) remains inadequate at providing sufficient information required to support safe space operations [57]. While improvements to the SSN may take years, what can be done now, and likely at cheaper costs, is to perhaps implement a minimum capability for satellite trackability. With the continued absence of a minimum satellite trackability, a large influx of potentially uncooperative satellites via commercial satellite mega-constellations "will increasingly strain [the] DOD's ability to provide actionable [space awareness] services" [57].

F. CONCLUSION

The most significant takeaway from the pre-launch management of commercial satellite mega-constellations within the United States is the absence of minimum thresholds for satellite size, maneuverability, and trackability. While the era of "old space" may not have required such thresholds, concerns stemming from the growing commercial utilization of satellite mega-constellations in today's "new space" suggest the need for U.S. pre-launch management processes to go beyond just satellite launch, communication, and remote sensing. Although thresholds pertaining to satellite design can potentially hinder innovation, their absence may lead to worsened conditions that threaten the safety and long-term sustainability of LEO. The question now is not *if* the United States needs more stringent requirements for the pre-launch management of commercial satellite mega-constellations, but rather *how* the United States can implement more stringent requirements without hindering growth of the commercial space industry.

THIS PAGE INTENTIONALLY LEFT BLANK

III. ON-ORBIT MANAGEMENT

A. INTRODUCTION

The on-orbit management of commercial satellites enables satellites to safely and efficiently conduct operations once launched. Primary on-orbit management activities are space situational awareness (SSA) and space traffic management (STM). At the international level, numerous entities and documents provide guidance for on-orbit management activities. However, the list, like in the case of pre-launch management, narrows when only considering those that mandate compliance from U.S. commercial satellites. COPUOS and the ITU-R are the only international entities that mandate compliance while the OST and RR are the only two international documents that mandate compliance. Furthermore, these management mechanisms only focus on ensuring peaceful space activities or interference-free communications. As a result, there is a significant lack of formalized verbiage at the international level for the on-orbit management of day-to-day commercial satellite operations [104]. Furthermore, few formal international rules and intents practically transfer to the national level within the United States for implementation on U.S. commercial satellites. Perhaps as an effect, there is currently no formalized national-entity solely dedicated to SSA and STM within the United States [57]. Instead, on-orbit management is primarily a shared effort among all U.S. space entities, both governmental and non-governmental. Therefore, current U.S. on-orbit management processes are oriented to ad-hoc problem solve and facilitate casual means of communication (e.g., phone calls and emails [107]). Although there is an absence of a formal on-orbit management regime at the national level, two entities provide a degree of "national" on-orbit management services—the 18th Space Control Squadron (18 SPCS) and the FCC. This chapter identifies and describes key entities, pertinent documents, current processes, and significant areas of concern within the U.S. on-orbit management framework.

B. SIGNIFICANT ENTITIES

Several significant entities involved in the pre-launch management segment (discussed in Section B of Chapter II) remain involved in the on-orbit management of commercial satellites. At the international level, several entities are involved in the on-orbit management of U.S. commercial satellite mega-constellations to varying degrees. Among these entities, only COPUOS and the ITU-R possess the authority to prescribe national-level requirements and are thereby able to mandate compliance from U.S. commercial satellites. Although COPUOS and the ITU-R primarily operate through binding requirements, three international entities contribute to the on-orbit management of U.S. commercial satellite mega-constellations via non-binding guidelines and best practices—the IADC, SSC, and Space Data Association (SDA). While the IADC and SSC both passively provide on-orbit management through voluntary guidelines, the SDA actively provides on-orbit management through conjunction assessments and warning services [2]. At the national level within the United States, the 18 SPCS and FCC conduct a degree of "national" on-orbit management of commercial satellites and mega-constellations although there is no formal regime at the national level.

1. International Entities

- Although **COPUOS** does not actively manage satellite activities, the discussions and resulting resolutions of COPUOS have established a broad international framework that outlines appropriate behaviors and activities in space. Regarding the on-orbit management of U.S. commercial satellites, COPUOS prescribes mandatory requirements (i.e., OST) and provides advisable guidelines (i.e., LTS Guidelines and the Space Debris Mitigation Guidelines of COPUOS) that promote safe behaviors in space. Additionally, COPUOS addresses any legal issues that might arise from on-orbit space activities [46].

- The **ITU-R** ensures the "rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services" including those that utilize satellite orbits [51]. As such, and relevant to the on-orbit management of U.S. commercial satellite mega-constellations, the ITU-R leverages its International Monitoring System (IMS), composed of "monitoring stations and centralizing offices voluntarily designated by administrations" [108], to conduct "monitoring & enforcement" activities [109]. These activities include "verifying the use of the spectrum in conformity with licenses conditions" [109] and assisting with the resolution of RF interference (RFI), among others [110].

- The **IADC** facilitates information exchange and fosters international cooperation in orbital debris research, space activities, and the development of debris mitigation responses and techniques [2], [56]. Serving as a "multi-lateral [forum] to coordinate efforts on space activities" [57], the IADC maintains and offers a voluntary collection of advisable measures for on-orbit satellite activity that enhances safety and mitigates orbits debris (i.e., the IADC Space Debris Mitigation Guidelines).

- The **SSC** adopts and improves on "international standards, guidelines, and practices" relevant to space safety [58] to "promote safe and sustainable space operations" [2]. Although a recently established space industry organization, the SSC actively maintains and offers a voluntary collection of advisable best practices for on-orbit satellite activity that enhances space safety (i.e., the Best Practices for the Sustainability of Space Operations).

- The **Space Data Association (SDA)**, established in 2009, is an "international organization that brings together satellite operators to support the controlled, reliable and efficient sharing of data critical to the safety and integrity of the space environment" [111]. The SDA aims to improve on-orbit safety as well as the sharing, accuracy, and timeliness of flight data and collision warnings [111]. While the SDA does not prescribe national requirements like COPUOS or the ITU-R nor offers a voluntary collection of rules like the IADC or SSC, the space "industry consortium" [2] provides its members a number of SSA and STM services [3] like "shar [ing] information on orbital positions and notif [ying] commercial and government members of collision risk" [2]. Members of the SDA include both civil and commercial satellite operators as well as "the world's major satellite communications companies" [111].

2. National Entities

- The **18 SPCS** is a unit within the recently established Delta 2 (DEL 2) of the U.S. Space Force (USSF) under the Department of Defense (DOD) [112]. The 18 SPCS is a continuously functioning entity, operating 24 hours a day and 7 days a week, that tasks and utilizes the DOD's SSN to generate spaceflight safety data [112] and to conduct "advanced analysis, sensor optimization, conjunction assessment, human spaceflight support, reentry/break-up assessment, and launch analysis" [113]. While the 18 SPCS is primarily responsible for Space Domain Awareness [112], which is distinct from SSA in that it focuses on national security and thus incorporates intent [114], it provides SSA data and services to both DOD and non-DOD space entities including commercial satellite operators [112].

- The **FCC** is overall responsible for managing and administering portions of the RF spectrum for non-federal use [115]. As such, the FCC "coordinate [s] and synchronize [s] frequency spectrum traffic to prevent or mitigate interference" [2], "investigates and resolves interference" [116], and handles "domestic non-compliance of spectrum use" [2] by investigating potential violations [116], [117].

C. PERTINENT DOCUMENTS

Similar to the case of significant entities, several pertinent documents relevant to the pre-launch management segment (discussed in Section C of Chapter II) remain relevant in the on-orbit management of commercial satellites. At the international level, numerous documents are involved in the on-orbit management of U.S. commercial satellite mega-constellations. Among these documents, only the OST and RR prescribe national-level requirements and mandate compliance if applicable to U.S. commercial satellites. Although the OST and RR are binding documents, there are several international, non-binding documents that contribute to the on-orbit management of U.S. commercial satellite mega-constellations—the LTS Guidelines, Space Debris Mitigation Guidelines of COPUOS, IADC Space Debris Mitigation Guidelines, and Best Practices for the Sustainability of Space Operations. In the United States, however, current national-level documents significantly lack verbiage for the on-orbit management of commercial satellite mega-constellations.

1. International Treaties, Agreements, and Principles

- The **OST** outlines broad principles for appropriate behaviors and activities in space to promote international cooperation on peaceful space activities. Regarding the on-orbit management of commercial satellites, the OST establishes basic principles of liability (i.e., Article VII), ownership (i.e., Article VIII), safety (i.e., Article IX), and information sharing (i.e., Article XI). While these Articles do not specifically describe activities for on-orbit management, they collectively establish a "basic framework on international space law" [118] through which inappropriate space behaviors are more identifiable than appropriate ones.

- The **LTS Guidelines** "promote and ensure the long-term sustainability of space activities" [72] through a collection of advisable practices in all three segments of satellite management. Specifically relevant to the on-orbit management of commercial satellites is Guideline B in which COPUOS provides guidelines for the "safety of space operations" such as establishing effective means of coordination to "facilitate effective responses to orbital collisions," utilizing "common, internationally recognized standards to enable collaboration and information exchange," and performing conjunction assessments "for all spacecraft capable of adjusting trajectories during orbital phases of controlled flight," among others [71].

- The **Space Debris Mitigation Guidelines of COPUOS** provides broad guidelines that mitigate orbital debris in the "mission planning, design, manufacture and operational (launch, mission, and disposal) phases" of satellites [76]. Pertinent to the on-orbit management of commercial satellites, the document advises satellite operators to minimize debris released during normal operations (Guideline 1) and conduct on-orbit satellite maneuvers to avoid collisions (Guideline 3) [76].

- The **IADC Space Debris Mitigation Guidelines** describes "existing practices that have been identified and evaluated for limiting the generation of space debris in the environment" [33] and offers a voluntary collection of mitigation measures that limit orbital debris. For the on-orbit management of commercial satellites, the document provides measures for limiting debris released during normal operations (i.e., Mitigation Measure 5.1), minimizing the potential of on-orbit mission breakups (i.e., Mitigation Measure 5.2), and preventing on-orbit collisions (Mitigation Measure 5.4) [33].

- The **Best Practices for the Sustainability of Space Operations** addresses "gaps in current space governance and [promotes] better spacecraft design operations and disposal practices aligned with long term space operations sustainability" [58]. Regarding the on-orbit management of commercial satellites, the document provides advisable information that is more specific for on-orbit satellite operations, unlike debris mitigation guidelines, and therefore provides detailed best practices for information exchange and safe space operations [77].

2. National Laws, Regulations, and Directives

- **Space Policy Directive – 3, National Space Traffic Management Policy (SPD-3)**, issued in June 2018, calls for "a new approach to space traffic management" in recognition of the growing global challenges to spaceflight safety [119]. Among the numerous space-related items addressed, the directive emphasizes the need for improved SSA and STM capabilities [119]. In addition, SPD-3 also designates the DOC as the civil agency responsible for providing "the publicly releasable portion" of the DOD's space object catalog and STM services not related to national defense [119].

D. KEY PROCESSES

After U.S. commercial satellites launch and integrate with their mega-constellations in LEO, SSA and STM activities enable the safe and efficient operations of satellites. However, as a result of the United States lacking a formal on-orbit management regime, SSA and STM is a shared effort among all those involved in the space domain. Although the 18 SPCS provides a degree of "national" on-orbit management services through activities like tracking satellites and alerting satellite operators of potential hazards [2], it is by no means the be-all and end-all of on-orbit management.

1. Space Situational Awareness

As defined by SPD-3, SSA is the "knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities" [119]. SSA, along with its associated activities and data, is a fundamental component of on-orbit management as it provides the foundation for STM activities [3] and supports "decision-making processes with quantifiable and timely body of evidence (predictive/ imminent/forensic) of behavior(s) attributable to specific space domain threats and hazards" [2]. Within SSA, there are three major areas of activity: (1) surveillance and tracking, (2) conjunction assessment and catalog maintenance, and (3) environmental data [2]. Each area provides an essential service of characterizing an element of the space operating environment. Although there is no active national SSA regime in the United

States, the DOD'S 18 SPCS currently provides "national-level" SSA services like tracking satellites and alerting satellite operators of potential hazards.

a. Surveillance and Tracking

Within the Surveillance and Tracking component of SSA, the core effort is maintaining positional information of space objects which requires the collection of data from sensors [2]. While there are several different types of sensors available (e.g., optical, radar, radio frequency, laser [2]), the primary sensor types for observing Earth-orbiting objects are optical and radar [120]. In any case, these instruments observe space objects, collect observations, and provide the information to an entity for processing [2]. The provided observations, or tracking SSA data, fall into one of two categories: metric data or characterization data [3]. Metric data are "observations of space objects that are combined to determine orbital trajectories" while characterization data are "measures of size, shape, broadcast frequencies, brightness, and other data that provide information about a space object's composition and capabilities" [3]. Upon collection of a space object's "position, characteristics, and trajectory," the SSA tracking data is then provided to space entities for processing and analysis [120].

In the United States, the DOD is the primary provider of "national" SSA, one that encompasses all U.S. satellites, and does so through its SSN [62]—the largest and most comprehensive sensor network in the world [3], [121]. The DOD's SSN is an extensive network of more than 30 ground- and space-based radars as well as telescopes [3] that synchronously work together to "search, discover, track, and characterize (SDTC) space objects" [2]. While the SSN primarily utilizes phased array radars and optical telescopes for its ground-based collection, it also employs "a few mechanical tracking radars" [121] as well as the recently established Space Fence radar which became operational in March 2020 [122]. Figure 5 depicts the locations and names of the various sensors belonging to the SSN. Once the SSN collects tracking SSA data, the information flows to Vandenberg Air Force Base in California where the 18 SPCS begins the next step of processing, analyzing, and cataloging the information [3].

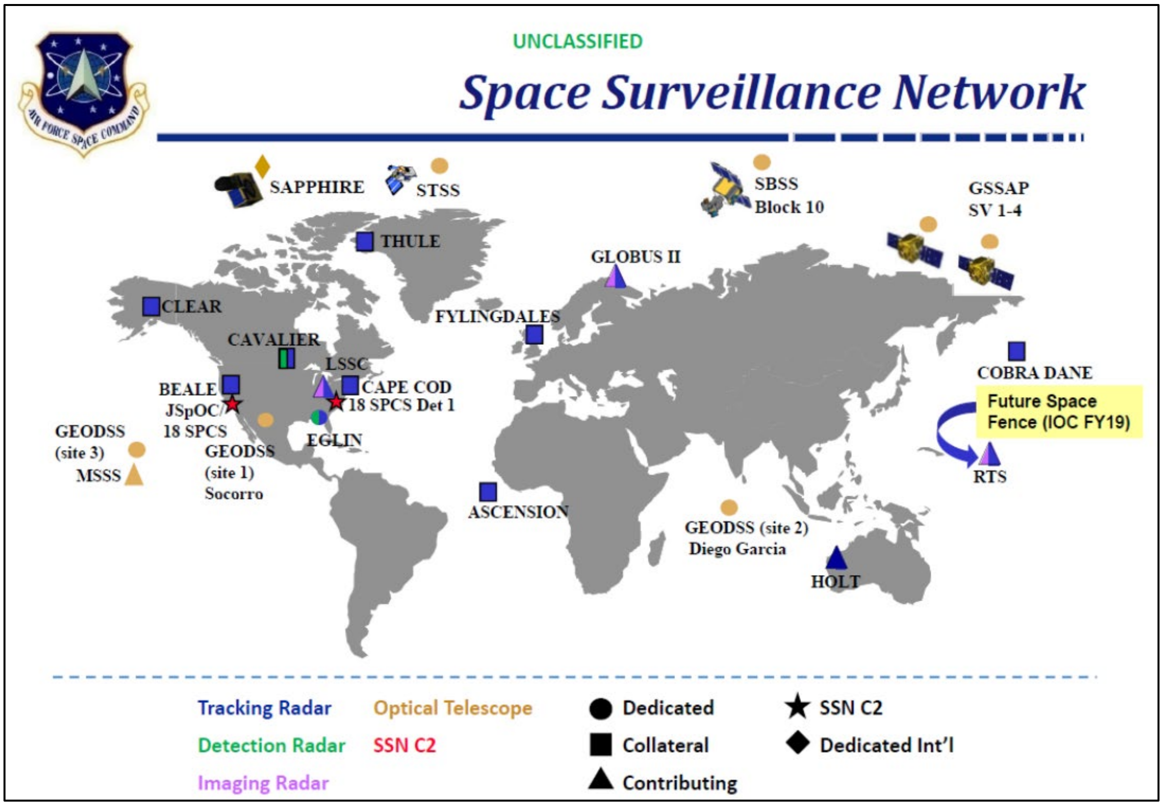

Figure 5. Global Distribution of SSN Sensors. Source: [57].

However, the SSN was designed to perform national security missions like missile warning and the defense of DOD satellites [2]. Additionally, the SSN came about "an era where there were relatively few objects in space, typically operating in predictable orbits and engaging in predictable activities" [2]. Within this context, the current national-SSA service provided by the DOD's surveillance and tracking activities is insufficient. Although the SSN persists in performing "national-level" surveillance and tracking activities, numerous other entities contribute to this effort. For example, there are civil space entities, commercial SSA companies, academic and research institutions [2], and commercial satellite operators [57] that provide SSA data or services. Among these entities, the largest contributors are commercial SSA companies and satellite operators themselves [57]. Prominent commercial SSA companies include ExoAnalytic Solutions, Rincon Research Corporation, SRI International [57], and LeoLabs.

b. *Conjunction Assessment Screenings and Catalog Maintenance*

Among the many SSA products and services produced in result of surveillance and tracking activities, the two most significant items are conjunction assessments and catalog maintenance. Within this component of SSA, the core effort is consistently maintaining an accurate catalog of resident space objects (RSOs) to "provide a variety of services and functions" [3] among which are conjunction assessments. As defined by NASA's Conjunction Assessment Risk Analysis (CARA) program, a conjunction, also known as a close approach, is "a local minimum in the difference between the position components of two trajectories - the closest point of approach" [123]. Figure 6 depicts a visual description of a conjunction/close approach. Furthermore, NASA's CARA program defines a conjunction assessment (CA) as "the process of predicting the conjunction event by screening the ephemeris of the protected asset against the space object catalog" [123]. There are several key steps to this process.

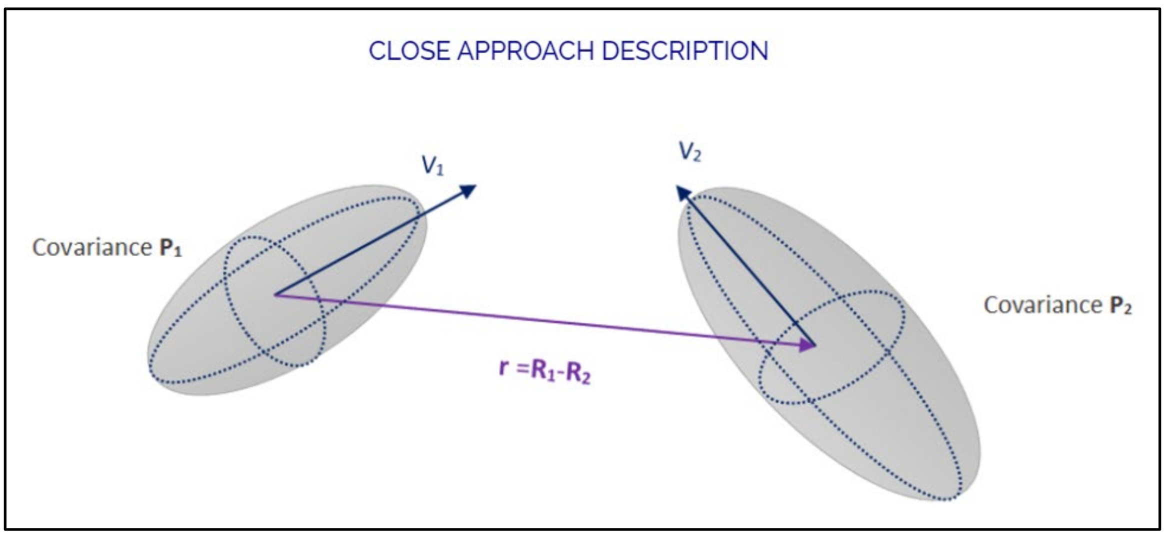

Figure 6. Close Approach Description. Source: [123].

The first step within the CA development process is orbit determination (OD) which is the process of computing orbital parameters to include covariance realism and ephemeris generation [2]. OD is "performed automatically multiple times per day to determine the position and velocity of each object" [124]. Second, results of OD are used to update the High Accuracy Catalog (HAC) [124] which provides a foundation for further analyses by the 18 SPCS [57]. Currently, the 18 SPCS maintains two catalogs: the HAC and the two-line element (TLE) catalog [57]. The HAC is a non-public catalog, perhaps due to proprietary content relating to covariance, and is “a compilation of special perturbation element sets that are stored in state vector format with associated covariance” [57]. The TLE catalog is a public catalog and “consists of extrapolated general perturbation (eGP) element sets that are stored in TLE set format without covariance, generated from the HAC” [57]. While the TLE catalog does not include covariance and, as a result, “may not be optimal for advanced analysis and risk assessment,” the catalog does provide adequate accuracy for “satellite operators and the space community to maintain knowledge of the general location of an object” [57]. Information within the TLE catalog is available to the general public via the website—Space-Track.org [57].

Third, the 18 SPCS then utilizes “the HAC to screen the orbital trajectories of all RSOs against all other RSOs, to include active satellites and non-active objects (debris, rocket bodies, dead payloads, etc.)” [124]. Currently, the 18 SPCS conducts three types of screenings: (1) HAC vs. HAC, (2) Owner/Operator (O/O) Ephemeris vs. HAC, and (3) O/O Ephemeris vs. O/O Ephemeris [124]. In short, each type of screening involves a different pair of data that are screened against each other to identify a conjunction. For instance, an “O/O Ephemeris vs. HAC” involves screening “ephemeris provided by the satellite owner/operator” against “the SP catalog data for all RSOs” [124]. It is noteworthy to mention, however, that a CA does not definitively provide a “yes” or “no” conclusion on whether a collision will occur between two objects in orbit [3]. Furthermore, due to the “numerous uncertainties present in each input,” a CA currently, at best, only provides a probability of collision [3].

Lastly, the 18 SPCS notifies relevant satellite operators of conjunctions if the events meet certain basic reporting criteria [124]. Pertinent to commercial satellite mega-constellations, satellite operators will receive a conjunction data message (CDM) from the 18 SPCS if they are involved in a conjunction where the time of closest approach (TCA) is less than or equal to 3 days and the overall miss distance is less than or equal to 1 km [124]. However, satellite operators will receive a CDM and a close approach notification

(CAN) email if they are involved in a "Emergency Criteria" conjunction where the TCA is less than or equal to 3 days, the overall miss distance is less than or equal to 1 km, and the probability of collision (Pc) is greater than or equal to 1x10^-4 [124]. In the event where satellite operators are involved in a "Emergency Phone Call Criteria" conjunction where the TCA is less than or equal to 3 days, overall miss distance is less than or equal to 1 km, and the Pc is greater than or equal to 1x10^-2, the 18 SPCS will provide a CDM, CAN email, and a phone call only if the involved objects are RSOs in the HAC [124]; O/O Ephemeris vs. O/O Ephemeris screenings do not apply to "Emergency Phone Call Criteria" [124]. Table 2 provides the basic reporting criteria for the 18 SPCS.

Table 2. 18 SPCS Basic Reporting Criteria for Conjunctions. Source: [124].

	Space-Track Criteria	Emergency Criteria	Emergency Phone Call Criteria
Notification Method	Conjunction Data Message (CDM)	Conjunction Data Message (CDM) & Close Approach Notification (CAN) email	CDM, CAN email & phone call
Deep Space HAC	TCA ≤ 10 days and Overall miss ≤ 5km	TCA ≤ 3 days and Overall miss ≤ 5km	TCA ≤ 3 days and Overall miss ≤ 500m
Deep Space O/O Ephemeris	TCA ≤ 10 days and Overall miss ≤ 5km	TCA ≤ 3 days and Overall miss ≤ 5km	N/A
Near Earth HAC	TCA ≤ 3 days and Overall miss ≤ 1km	TCA ≤ 3 days & Overall miss ≤ 1km & Probability of Collision ≥ e^-4	TCA ≤ 3 days and Overall miss ≤ 1km and Probability of Collision ≥ e^-2
Near Earth O/O Ephemeris	TCA ≤ 3 days and Overall miss ≤ 1km	TCA ≤ 3 days & Overall miss ≤ 1km & Probability of Collision ≥ e^-4	N/A

c. Environmental Data

Within the Environmental Data component of SSA, the core effort is evaluating the space operating environment's natural dynamics: space weather, micrometeoroids, asteroids, Earth's timing and orientation parameters, solar flares, and coronal mass ejections (CMEs) [2], [125]. Proper evaluation of environmental data, such as solar dynamics [125], can provide insight into the potential negative effects of the natural space environment on U.S. commercial satellites and their operations. At the national level in the United States, NOAA and NASA work together in evaluating the natural space environment [2]. NOAA is currently "the nation's primary source of space-based meteorological and climate data" [2] and is a key source of environmental data. NASA not only provides environmental data, but also evaluates and models the information [2]. In addition, commercial and academic entities contribute to the sourcing and evaluation of environmental data [2]. Environmental data is collected and used to better understand the current space operating environment and to support STM activities in appropriately managing space assets.

2. Space Traffic Management

As defined by SPD-3, STM is the "planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment" [119]. STM, along with its associated activities and services, is a fundamental component of on-orbit management as it enables "safety driven maneuvers, meant to protect our most important space assets" [105]. STM activities, supported by SSA activities and associated data [42], ultimately aim to prevent and mitigate on-orbit conjunctions or collisions between two space objects [2]. Similar to SSA, STM is a shared effort among all those involved in the space domain. While the DOD conducts a fraction of STM by providing on-orbit safety information and services [126], it does not operate in any regulatory or authoritative capacity for non-DOD space objects like commercial satellites. Thus, the DOD can only notify satellite operators of potentially hazardous events [2]. Furthermore, it is the choice of satellite operators to maneuver or not maneuver their satellites [2]. Within STM, there are four major components: (1) space traffic coordination and safety, (2) collision avoidance risk assessment, (3) collision mitigation, and (4) frequency deconfliction [2].

a. Space Traffic Coordination and Safety

Within the Space Traffic Coordination and Safety component of STM, activities primarily involve creating conditions that enable "effective data exchange and ongoing interaction between space operating stakeholders" and coordinating space activities among different space entities [2]. Currently, the DOD is the only federal entity that facilitates and promotes on-orbit "operator synchronization and coordination" [2] in regard to the management of commercial satellites. Even so, because the DOD does not possess any regulatory authority over commercial satellite activities [62], the level of coordination is ultimately at the discretion of satellite operators.

b. Collision Avoidance Risk Assessment

Within the Collision Avoidance Risk Assessment component of STM, activities include "collision likelihood assessments, collision consequences assessments, and data actionability" [2]. Again, the DOD is the only federal entity to perform on-orbit "collision risk assessment and management" [2] in regard to the management of commercial satellites. On behalf of the DOD, the 18 SPCS executes "on-orbit conjunction assessment and collision avoidance" among several other spaceflight safety items [57]. While NASA also conducts collision avoidance and risk assessments, the assessments pertain specifically to human spaceflight activities such as ISS operations [2].

c. Collision Mitigation

In the Collision Mitigation component of STM, involved activities entail synchronization and maneuver planning operations to avoid conjunctions or collisions [2]. While the DOD, via the 18 SPCS, provides some level of national oversight for collision mitigation by tracking satellites and notifying space entities of concerning events [2], collision mitigation is ultimately a communal endeavor. Because there is "no actively managed space traffic management system in the United States" [57], the majority of, if not all, satellite operators utilize their own methods and processes to evaluate and perform collision mitigation to protect their assets [57]. Again, because of the significant lack of any formalized architecture for national-level STM, satellite operators currently resolve collision events by communicating primarily through phone calls and emails [107].

d. Frequency Deconfliction

In the Frequency Deconfliction component of STM, involved activities entail the coordination and synchronization of the RF spectrum to mitigate or prevent RFI [2]. As discussed in Section B of this chapter, the FCC is responsible for managing and ensuring compliant RF spectrum use by U.S. commercial satellites [2].

E. AREAS OF CONCERN

Today, a formal national-level entity that manages on-orbit commercial satellites is largely absent. Although the 18 SPCS provides a degree of "national-level" SSA services, the 18 SPCS is neither formally recognized as "the" provider of national SSA nor formally empowered to authoritatively act on SSA data. As such, the safety of active satellites and their operations are entirely dependent on the responsibleness and proactiveness of satellite operators. While this framework for management may have been adequate to oversee the satellites of "old space," it is significantly challenged by the proliferated commercial satellite mega-constellations of "new space." Current absences of rules for the day-to-day operations of satellites, common definitions for on-orbit management activities, and formal entities for national SSA and STM are likely to strain on-orbit management efforts as commercial satellite mega-constellations usher in hundreds to thousands of satellites in LEO.

1. Absence of Rules for Day-to-Day Satellite Operations

Currently, there are no national-level documents or entities that implement a "rules of the road" concept in space for commercial satellites, or all U.S. satellites for that matter, much like those exercised in today's motorways, airways, and waterways. The absence of such rules primarily derives from the fact that "most of an operator's conjunctions in LEO remain with inactive objects" and "conjunctions between operational satellites [are] so rare that simple person-to-person communication [is] a low burden" [107]. As such, satellite operators, in avoiding conjunctions or collisions, have so far "been best able to determine the mitigation action appropriate to their mission" [107]. Furthermore, satellite operators "have typically opposed external maneuver directions" primarily because of "varying mission constraints and unique maneuver capabilities" [107]. While this may currently be the case, the number of new satellite operators and satellites ushered in by commercial satellite mega-constellations may now require rules that explicitly outline appropriate protocols for day-to-day satellite operations.

As a result of the trends associated with "new space," today's satellite operators can no longer operate "under a 'big sky' assumption" as "close approaches, proximity operations, and even collisions occur with alarming, rising frequency" [67]. Furthermore, as one study states, there are a number of new satellite operators who have not yet established a foundation of "what works best for their operations" or "developed long-standing procedures, best practices and norms of behavior" [41]. As the number of satellite operators and satellites increase in the LEO operating environment, the absence of a national set of rules and protocols for day-to-day satellite operations may lead satellite operators, particularly "new space" operators, to inadvertently maneuver into a potential conjunction or collision which is becoming increasingly more probable as the rise in orbital debris population may require avoidance maneuvers.

2. Absence of Common Definitions for On-Orbit Management

As reported by the Institute for Defense Analysis (IDA) in an April 2018 study, "there is little commonality in the definitions of SSA and STM across different entities and stakeholders" [57]. Although the scope of the study included the international domain, the document clearly revealed a disparity in the definitions of SSA and STM even among U.S. space entities. Although SPD-3 explicitly provided definitions for both SSA and STM when it was issued in June 2018, the definitions of SSA and STM still varied two years later when NAPA reported a "widespread variation in definitions of core terms" [2] in an August 2020 study. Currently, numerous space entities possess their own definitions [57] which can hinder future developments or operations in the on-orbit management of commercial satellites and constellations. For instance, due to the absence of common definitions of SSA and STM, the terms are "often used interchangeably" [57]. As a result, varying "decision-making and maneuvering processes" [57] can leave satellite operators vulnerable to misinterpretation and false assumptions when attempting to conduct constructive or even time-sensitive dialogue. Furthermore, the absence of common definitions for SSA and STM can lead to fundamentally different methods, processes, and capabilities which has already taken place among commercial space entities [57]. While there is nothing particularly wrong with differing SSA/STM approaches, such differences not rooted in common definitions can be damaging to future developments or operations in the on-orbit management of commercial satellite mega-constellations as there is no agreement in the "capabilities that constitute SSA/STM functions" [2].

3. Absence of a Formal and Empowered Entity for National SSA

From searching and tracking space objects to assessing conjunctions and notifying satellite operators, the 18 SPCS provides a spectrum of much needed SSA-related services to all U.S. satellite operators [62]. While this informal structure for “national-level SSA” may have been adequate for the “old space” operating environment, “new space” satellite populations and activities suggest a need for a more robust SSA framework. For instance, an April 2016 report by the DOT found that “about 70% of close approaches involving active satellites in orbit involve commercial systems” [62]. This means that as the commercial utilization of satellite mega-constellations increases, the 18 SPCS’ already demanding task will only become more difficult.

Recognizing both the burden on the DOD and the fact that its services to commercial space entities “is not necessarily an inherently military mission” [62], President Trump, in June 2018, signed SPD-3 which directed the DOC to take on the U.S. Air Force’s (USAF’s) role of providing non-defense SSA and STM services. However, the transition has been sluggish with no provision of “funding and authorities” for the DOC from Congress even in November 2020. Although Congress approved a moderate “budget boost” for the DOC in the following month for FY2021, the Office of Space Commerce (OSC) was not elevated “from NOAA into the office of the Secretary of Commerce” where it was hoped that the OSC “would evolve into a Bureau of Space Commerce” [127]. As such, the OSC currently continues to “[work] within its limited resources” [127].

The lack of empowerment shown to the 18 SPCS and now to the OSC, in both authority and budget, is alarming considering the dire need for an effective national SSA entity. The sheer number of new satellites expected to be present in LEO over the next decade [9] ultimately means increased difficulties in conducting SSA which threaten the United States’ ability in ensuring safe space operations. Yet, there remains an absence of a formal and empowered entity for national SSA.

4. Absence of a Formal and Authoritative Entity for National STM

The increased numbers of space entities, active satellites, orbital debris, conjunctions, and potential collisions require satellite operators to concentrate efforts on safely maneuvering satellites and effectively communicating with one another. While this may be the case, the safe maneuvering of satellites and effective communication of satellite operators can prove difficult without an authoritative entity for national STM. Operators desiring to maneuver their satellites, whether it be for getting on-orbit for operations, conducting on-orbit activities, or de-orbiting for post-mission disposal, must now be keen to two significant considerations. First is increased numbers of active satellites and orbital debris which, even if non-maneuvering, no longer permit satellite operators to maneuver however and whenever they please. Maneuvers for mitigating conjunctions or avoiding collisions can potentially lead operators to redirect their satellites into the trajectories of another object. Second, the increased volume, diversity [128], and complexity of space activities [9] (e.g., rendezvous proximity operations (RPOs), "satellite servicing, debris removal, in-space manufacturing, and tourism" [128]), inevitably means that the space operating environment will only become more dynamic. As such, operators must be highly aware and vigilant of the activities and intentional maneuvers of other satellites. Adding to these difficulties are the addition of commercial satellite mega-constellations and the absence of a formal and authoritative entity that can provide direction if needed.

While some may believe that the issues with safely maneuvering satellites can be corrected with improved communication among satellite operators, communication is also another problem. Although the nature of "simple person-to-person communication [is] a low burden" and should be rather efficient and direct, "not all operators have been willing or able to communicate within the few days prior to the time of close approach" [107]. As a result, satellite operators have been forced to take drastic measures as was the case in 2019 when an Aeolus satellite maneuvered (increased its altitude) around a Starlink satellite to avoid a close approach that had a Pc of 1 in 1,000 [107], [129], [130]. For events that provide even shorter times for response, the current means of communications is not enough. Making matters worse, the growing commercial utilization of satellite mega-constellations means there will inevitably be more new satellite operators that are relatively unfamiliar with the space operating environment, its standard communication struggles, and industry-implied means of communication as there are no space traffic rules. Furthermore, the absence of a formal and authoritative entity for national STM means that both new and experienced satellite operators do not have a credible resource for advisable direction after failing to establish communication with appropriate operators.

Even then, some may believe that today's satellite operators have enough space data available to not require direct or immediate communication with other operators. However, there are also issues with space data. For many satellite operators, the 18 SPCS provides needed SSA data and services. However, there is currently a general consensus among space entities that "the currently provided situational awareness information is limited and insufficient" [2]. SSA data like "realistic covariance data" and "compatible force model settings" along with debris and satellite sizes, dimensions, masses, and altitudes are all currently insufficient or largely unavailable [67]. As a result of either insufficient or unavailable data along with an absence of space traffic rules, satellite operators may be forced to conduct ineffective collision avoidance maneuvers [131] that ultimately leads to collisions or the enabling of collisions.

While issues already exist with ensuring the safe maneuvers of satellites and effective communications of satellite operators, the addition of commercial satellite mega-constellations in the space operating environment certainly does not improve the outlook. Even with the 18 SPCS' support to commercial satellite operators in conducting on-orbit activities, the absence of a formal and authoritative entity for national STM leaves satellite operators to ultimately decide for themselves whether or not to conduct collision avoidance maneuvers [2]. Furthermore, there is no assurance that satellite operators will make the "right" call especially because of the increasing dynamic of the space operating environment. This is not only a potentially dangerous predicament for involved satellite operators, but is also a scenario which can negatively impact all satellite operators operating in space. Regardless of whether a more structured STM regime arises as a single authority or several authorities within the United States, some level of a "central space traffic management authority" [107] must exist to better coordinate and monitor satellite maneuvers, facilitate communication, and provide advisable direction if needed.

F. CONCLUSION

The most significant takeaway from the on-orbit management of commercial satellites within the United States is the general absence of a governing presence. The current on-orbit architecture remains outdated and oriented for a time when there were significantly fewer space objects and entities. To mitigate the adverse effects of the increasing presence of commercial satellite mega-constellations in LEO, standing forms of management, whether by entities or bodies of rules, must evolve and incorporate the day-to-day operations of commercial satellites and constellations. Domestic SSA and STM entities, definitions, methods, processes, and capabilities must formalize to address larger issues like on-orbit management framework and structure. Without such efforts and management, commercial satellite mega-constellations can exacerbate current or expected problems in LEO.

IV. POST-MISSION MANAGEMENT

A. INTRODUCTION

The post-mission management of commercial satellites ensures the appropriate safing and disposal of expended satellites [2]. Involved activities include reviewing and evaluating plans for post-mission disposal (PMD) [39] and induced risks as well as monitoring and confirming the results of post-mission activities [45]. These activities ultimately mitigate the generation of new orbital debris and sustain the long-term sustainability of the space operating environment. While several international entities and documents provide guidance for post-mission management activities, none mandate compliance from U.S. commercial satellites. Instead, existing international management mechanisms only promote desirable post-mission satellite activities. COPUOS, the IADC, and SSC are international entities that promote post-mission satellites activities. Regarding international documents that promote post-mission satellite activities, there are the Space Debris Mitigation Guidelines of COPUOS, IADC Space Debris Mitigation Guidelines, and Best Practices for the Sustainability of Space Operations. In the United States, however, the case is slightly different. The USGODMSP requires "all federal agencies that acquire or operate spacecraft [to] apply [the document's] principles directly" [62] and, as a result, the AST, FCC, and CRSRA all require plans for post-mission activities as part of their licensing processes [62]. Consequently, post-mission management at the national level within the United States primarily takes place in the pre-launch management segment where satellite operators' plans for satellite safing and disposal are reviewed and evaluated. Furthermore, the active presence of national-level post-mission management during physical satellite post-mission activities, aside from potentially monitoring and confirming the results thereof, is virtually absent.

B. SIGNIFICANT ENTITIES

Several significant entities involved in pre-launch and on-orbit management segments (discussed in Section B of Chapter III and Chapter IV, respectively) are also involved in the post-mission management of commercial satellites. At the international level, there are few entities involved in the post-mission management of U.S. commercial satellite mega-constellations. Although none mandate compliance from U.S. commercial satellites, COPUOS, the IADC, and SSC "manage" post-mission satellite activities through non-binding international documents that promote and promulgate desirable post-mission satellite activities. At the national level within the United States, the AST, Satellite Division, CRSRA, and 18 SPCS passively conduct the post-mission management of commercial satellites.

1. International Entities

- Although **COPUOS** does not necessarily conduct "hands-on" management of activities, the discussions and resulting resolutions of COPUOS have established a broad international framework that outlines appropriate behaviors and activities in space. Regarding the post-mission management of U.S. commercial satellite mega-constellations, COPUOS provides advisable guidelines (i.e., the LTS Guidelines and Space Debris Mitigation Guidelines of COPUOS) that promote the mitigation of orbital debris as well as the sustainability of space operations.

- The **IADC** facilitates information exchange and fosters international cooperation in orbital debris research, space activities, and the development of debris mitigation responses and techniques [2], [56]. Primarily focused on the mitigation of orbital debris, the IADC maintains and offers a voluntary collection of advisable measures for post-mission satellite activity (i.e., the IADC Space Debris Mitigation Guidelines).

- The **SSC** adopts and improves on "international standards, guidelines, and practices" relevant to space safety [58] to "promote safe and sustainable space operations" [2]. Primarily focused on the comprehensive safety of space operations, the SSC also maintains and offers a voluntary collection of advisable measures for post-mission satellite activity (i.e., the Best Practices for the Sustainability of Space Operations).

2. U.S. National Entities

- The **AST** regulates "the U.S. commercial space transportation industry to ensure compliance with international obligations of the United States" [60]. In regard to the post-mission management of commercial satellites, the AST is responsible for licensing satellite reentries [2]. As such, the AST requires satellite operators to obtain a license for reentry activities, if applicable, and prescribes the license in the pre-launch management segment. In addition, the AST supports the reentries of planned and approved satellites through "reentry predictions, safety analysis, and ground, maritime, and aviation safety and notices as well as orbital collision avoidance from orbit to reentry" [2].

- The **Satellite Division** licenses the use of the RF spectrum by U.S. commercial satellites [62]. Although primarily involved with commercial satellite mega-constellations in the pre-launch management segment, the Satellite Division, like the AST, requires satellite operators, as part of the RF licensing process, to submit plans and assessments for post-mission activities and orbital debris mitigation [2], [57], [62], [85].

- The **CRSRA** licenses U.S. commercial-spaced based remote sensing systems and operations [64]. Much like the Satellite Division, although the CRSRA is primarily involved with commercial satellite mega-constellations in the pre-launch management segment, it too requires satellite operators, those with remote sensing missions, to submit plans and assessments for post-mission satellite activities [57], [62], [86].

- The **18 SPCS** tasks and utilizes the DOD's SSN to generate spaceflight safety data [112] and conduct "advanced analysis, sensor optimization, conjunction assessment, human spaceflight support, reentry/break-up assessment, and launch analysis" [113]. In regard to the end-of-life management of commercial satellites, the 18 SPCS supports reentry operations through a spectrum of activities such as conducting assessments, monitoring reentries, and confirming breakups or reentries [112].

C. PERTINENT DOCUMENTS

Similar to the case of significant entities, several pertinent documents relevant to pre-launch and on-orbit management segments (discussed in Section C of Chapter III and Chapter IV) are also relevant to the post-mission management of commercial satellites. At the international level, there are few documents involved in the pre-launch management of U.S. commercial satellite mega-constellations. While none mandate compliance from U.S. commercial satellites, the Space Debris Mitigation Guidelines of COPUOS, *IADC Space Debris Mitigation Guidelines*, and *Best Practices for the Sustainability of Space Operations* provide voluntary guidelines and best practices that promote and promulgate desirable post-mission satellite activities. In the United States, however, there are national documents, although few, that support the post-mission management of commercial satellites. These national documents primarily mandate commercial satellite operators to provide plans and assessments for post-mission activities such as disposal strategies, risk assessments, and debris mitigation measures [57].

1. International Treaties, Agreements, and Principles

- The **LTS Guidelines** promote and ensure the long-term sustainability of space activities through a "set of 21 voluntary consensus Guidelines" [72]. While the document offers numerous considerations for safe space activities for all three management segments, it specifically provides Guideline B.9 which outlines measures that address the "risks associated with the uncontrolled re-entry of space objects" in post-mission activities [71].

- The **Space Debris Mitigation Guidelines of COPUOS** provides broad guidelines that mitigate orbital debris in the "mission planning, design, manufacture and operational (launch, mission, and disposal) phases" of satellites [71]. Regarding the post-mission management of commercial satellites, the document provides guidelines for minimizing the potential of post-mission breakups (Guideline 5) and limiting the post-mission generation of long-term orbital debris (Guideline 6) [71].

- The **IADC Space Debris Mitigation Guidelines** describes "existing practices that have been identified and evaluated for limiting the generation of space debris in the environment" [33] and offers a voluntary collection of mitigation measures that limit orbital debris. Like the Space Debris Mitigation Guidelines of COPUOUS, the IADC Space Debris Mitigation Guidelines also contributes to the post-mission management of commercial satellites through the provision of measures for minimizing the potential of post-mission breakups (Mitigation Measure 5.2.1) and conducting post-mission disposals (Mitigation Measure 5.3.2) [33].

- The **Best Practices for the Sustainability of Space Operations** addresses "gaps in current space governance and [promotes] better spacecraft design operations and disposal practices aligned with long term space operations sustainability" [58]. Specific to the post-mission management of commercial satellites, the document provides industry best practices for post-mission satellite activities such as maintaining specified satellite conditions that enable successful disposal and considering certain methods of satellite disposal [77].

2. National Laws, Regulations, and Directives

- The **USGODMSP** "establishes a framework for debris mitigation requirements" and mandates compliance from USG agencies and organizations while allowing those entities to "impose more specific or more stringent rules" [80]. In regard to the post-mission management of commercial satellites, the USGODMSP provides standard practices for the disposal of satellites "at the end of mission life to minimize impact on future space operations" (Objective 4) [78].

- **14 CFR, Chapter III** is the FAA's regulations on commercial space transportation activities and outlines requirements for commercial space companies desiring to obtain a license for launch and reentry operations. Regarding the post-mission management of commercial satellites, the document, as part of the initial licensing process, mandates several post-mission requirements from commercial satellite operators such as a reentry collision avoidance analysis which further requires operators to satisfy reentry conditions for probability of collision and spherical separation [83].

- **47 CFR, Chapter I** is the FCC's regulations on all telecommunications activities and outlines requirements for commercial space companies desiring to obtain a license for satellite communications. Regarding the post-mission management of commercial satellites, the document, as part of its initial licensing process, mandates commercial satellite operators to provide "a statement detailing the post-mission disposal plans for the [satellite] at end of life" [85]. Furthermore, details include any fuel "that will be reserved for post-mission disposal maneuvers," casualty risk assessments "if planned post-mission disposal involves atmospheric re-entry of the [satellite]," and assessments of reentry breakups [85].

- **15 CFR, Chapter IX, Part 960** is NOAA's regulations on commercial remote sensing activities and outlines requirements for commercial space companies desiring to obtain a license for space-based remote sensing activities. Regarding the post-mission management of commercial satellites, the document, as part of its initial licensing process, mandates commercial satellite operators to provide "plans and procedures" [62] of post-mission disposal for remote sensing satellites that are "satisfactory to the President" [86]. Although much more vague than the requirements prescribed in 14 CFR and 47 CFR, 15 CFR nonetheless incorporates post-mission management into its licensing process.

- **SPD-3** calls for "a new approach to space traffic management" in recognition of the growing global challenges to spaceflight safety [119]. While the document addresses several USG focuses for improving STM and spaceflight safety, SPD-3 specifically calls for the periodic revision and domestic enforcement of "debris mitigation guidelines, standards, and policies" to "mitigate the operational effects of orbital debris" [119]. SPD-3 also specifically invites both satellite and constellations operators to conduct post-mission disposals of their satellites [119].

D. CURRENT PROCESSES

As U.S. commercial satellites near the end of their mission lives in LEO, safing and disposal activities safely and efficiently remove expended satellites from their mega-constellations and operational orbits to mitigate the "collision threat to future space operations" [132]. The core focus of post-mission activities is the mitigation of orbital debris generation which ultimately reduces the likelihoods of conjunctions and collisions and thereby enables the long-term sustainability of space operations. As such, current U.S. post-mission management processes include reviewing and evaluating plans for PMD [39] and induced risks as well as monitoring and confirming the results of post-mission activities [45]. Although some post-mission processes do exist at the national level, they remain largely passive in that they manage post-mission activities through pre-launch requirements like plans and assessments. Furthermore, current post-mission processes are generally vague and limited in what they require from commercial satellite operators for post-mission activities.

1. General Satellite Safing and Disposal Activities

Satellite safing involves passivation which is the "process of removing stored energy from a space structure which could credibly result in eventual generation of new orbital debris after End of Mission" [132]. Intended to prevent and mitigate "accidental explosions" [132], the process includes activities like "removing energy in the form of electrical, pressure, mechanical, or chemical" from onboard satellite subcomponents [132]. For instance, LEO satellite operators may remove "residual propellants" remaining in the "attitude control system" of their satellites by conducting "propellant depletion burns" [132]. Collectively, these activities mitigate "the potential of self-induced fragmentation and limits debris generation consequences after a collision with a small Micrometeoroids and Orbital Debris (MMD) particle" [132]. According to NASA, the passivation of satellites "should occur as soon as such operation does not pose an unacceptable risk to the mission" [132].

Satellite disposal involves activities that either de-orbit or reposition expended satellites to effectively prevent or mitigate future conjunctions or collisions. According to NASA, there are three methods of satellite disposal: Earth atmospheric reentry, maneuvering to a storage orbit, and direct retrieval [132].

a. Earth Atmospheric Reentry

Earth atmospheric entry is a method of post-mission disposal that involves the "natural or directed reentry [of a satellite] into the atmosphere within a specified time frame" [132]. For a natural reentry, or natural decay, satellite operators can leave their satellite "in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of mission" [132]. The rate of decay for a satellite, the rate at which a satellite will reenter the Earth's atmosphere, is dependent on several factors like its orbit allocation and ballistic coefficient [133]. For a directed reentry, satellite operators can maneuver their satellite into "a controlled de-orbit trajectory" upon which the satellite can reenter the Earth's atmosphere [132]. In either case, satellite operators should ensure that they passivate their satellites before their satellites reenter the Earth's atmosphere [132]. As NASA states, a natural reentry is generally "the most energy-efficient means for disposal of space structure in orbits below 1400 km" [132].

b. Maneuvering to Storage Orbit

Maneuvering to a storage orbit is a method of post-mission disposal that involves the repositioning of a satellite to "one of a set of disposal regions in which the [satellite] will pose little threat to future space operations" [132]. With this method, satellite operators must maneuver their satellite "into an orbit with perigee altitude above 2000 km and ensure its apogee altitude will be below 19,700 km, both for a minimum of 100 years" [132]. This is due to the fact that objects in disposal orbits above 2000 km, and below Medium Earth Orbit (MEO), have a lower "probability of collision" which NASA currently calculates to be 1 per 1000 years [132]. NASA has also assessed that if a collision does occur in these disposal orbits, it is likely that "very little debris from that collision would come low enough to pose a significant threat to operational satellites in LEO" [132]. Currently, NASA recommends this method of disposal for satellites between 1400 to 2000 km [132].

c. Direct Retrieval

Direct retrieval, also known as active debris removal (ADR) [134], is a method of post-mission disposal that involves the retrieving of a satellite and returning it to Earth [132]. Although this method is difficult and not yet operational [30], [135], NASA recommends satellite operators to retrieve and remove their satellite from LEO "within 10 years after completion of mission" [132].

2. AST/FAA Post-mission Requirements

The AST/FAA are responsible for all commercial launches and reentries. As such, the AST/FAA, during its licensing process within the pre-launch management segment, requires commercial satellite operators to satisfy several post-mission conditions before granting operators a license to conduct post-mission reentry activities. Outlined in 14 CFR, Chapter III, Subchapter C, Part 450, there are two significant sets of requirements that specifically apply Earth reentries. The first set of requirements, titled "reentry risk criteria," requires satellite operators to assess and calculate the probabilities of the potential risks to the general public, individual entities, operating aircraft, and critical assets [83]. Currently, the AST/FAA mandates (1) an expected number of casualties for collective risk to be less than 1×10^{-4}, (2) a probability of casualty for individual risk to be less than 1×10^{-6}, (3) a probability of impact with operating aircraft to be less than 1×10^{-6}, and (4) a probability of loss of functionality to be less than 1×10^{-3} [83]. The second set of requirements, titled "launch and reentry collision avoidance analysis requirements," requires satellite operators to assess and calculate the probability of collision between reentering spacecraft and any other object, including orbital debris, as well as requiring reentering spacecraft to "maintain a spherical separation distance" from any other object

[83]. Currently, the AST/FAA mandates a probability of collision to be less than 1×10^{-5} and a spherical separation of 25 km [83].

3. Satellite Division/FCC Post-mission Requirements

Although the FCC is primarily responsible for RF spectrum management for satellites, it requires satellite operators to provide numerous "description [s] of the design [s] and operational strategies that will be used to mitigate orbital debris" [85]. Among these requirements, specifically relevant to post-mission activities are: (1) a statement that the satellite operator has "assessed and limited the probability, during and after completion of mission operations, of accidental explosions," (2) a demonstration that the satellite operator has "assessed and limited the probability of collision between [their satellite] and other large objects (10 cm or larger in diameter)" when de-orbiting, (3) a "demonstration that the probability of success of the chosen disposal method will be 0.9 or greater for any individual [satellite]," (4) a demonstration that the probability of success will be "0.99 or better" for any satellite apart of a large system, and (5) a "demonstration that the calculated casualty risk for an individual spacecraft using the NASA Debris Assessment Software or a higher fidelity assessment tool is less than 0.0001" [85].

4. De-orbit Support

Within the post-mission management of commercial satellites, the 18 SPCS is the only government entity to conduct active management of post-mission satellite activities. For satellite repositioning activities, the 18 SPCS can "assist [satellite operators] by screening maneuver ephemeris and providing results" of satellite end-of-life repositioning or disposal [124]. For satellite de-orbiting activities, the 18 SPCS can "provide CA screenings, as well as coordinate with NASA to ensure the deorbiting spacecraft safely descends through the International Space Station's orbit" and, after a satellite has completed its final maneuvers, "confirm final reentry" [124]. However, satellite operators must request these services from the 18 SPCS through the submission of an Orbital Data Request (ODR) along with maneuver plans and ephemeris data [124].

E. AREAS OF CONCERN

The U.S. post-mission management of commercial satellites ensures the appropriate safing and disposal of expended satellites [2]. However, current processes not only lack adequate levels of enforcement and accountability, they are inadequate at disposing current commercial satellites and addressing the growing number of satellites ushered into LEO by mega-constellations.

1. Lack of Active Post-mission Management and Enforcement

Although the 18 SPCS provides post-mission support services, only the AST, Satellite Division, and CRSRA formally manage satellite post-mission activities. However, these three federal entities only passively manage satellite post-mission activities as they require commercial satellite operators to provide associated plans and assessments before the satellites launch. Furthermore, the three federal entities do not have any processes in place to actively enforce the satellite post-mission plans they approved. As a result, "only 15–25 percent of payloads reaching end-of-life in LEO attempt to comply" with their initially proposed plans for post-mission activities like "de-orbit [ing] into the Earth's atmosphere within 25 years" [7]. Even then, "only 5–15 percent" result in successful de-orbits [7]. With the current lack of active post-mission management and enforcement at the national level, the rise in commercial satellite mega-constellations, if following the behaviors of the other 75–85 percent of non-complying payloads, is likely to result in a worsened space operating environment in which hundreds or even thousands of expended and abandoned satellites threaten the safety of space operations.

2. Inadequate Post-mission Lifetime Limits

While the "25-year rule" may have been sufficient to alleviate the orbital debris and active satellite balance in the past, today's commercial satellite mega-constellations significantly challenge the ability of the longstanding mitigation measure to actually mitigate orbital debris. As several studies now suggest, the current lifetime limit of 25 years for satellites in natural decays is inadequate for effective PMDs. For instance, one substantial 2019 study investigated the "linear growth of the orbital debris population … observed in the results of many evolutionary models … used to simulate the effects of the widespread adoption of the [IADC] debris mitigation guidelines" [39]. Within the study, the "Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) model was used to perform ultra-long projections of the future debris population ≥ 10 cm in [LEO] under highly optimistic debris mitigation conditions" [39]. The results revealed "that the linear growth rate observed for the first 200 years of the projection period was transient and the growth was exponential, even with the ongoing and widespread adoption of debris mitigation measures" [39]. Furthermore, the results also revealed "a tendency for high and sustained collision rates at altitudes below 700 km, predominantly due to conjunctions between spacecraft and upper stages decaying through this region in observance with the '25-year rule'" [39].

Although the previous study is fairly recent, the notion of the "25-year rule" being insufficient goes as far back as 2006 when NASA's Orbital Debris Program Office modeled and evaluated LEO's orbital debris environment. In the 2006 NASA study, the orbital debris environment of LEO was modeled with the assumption that "no satellites [would] be launched after December 2005" [8]. The results of the study revealed that LEO's debris environment had already reached a level where "even if no further space launches were conducted, the Earth satellite population would remain relatively constant for only the next 50 years" [8]. The study further revealed that beyond the 50-year timeframe, the number of orbital debris would increase noticeably over the next two centuries due to the high collision activity primarily occurring in the 900 to 1000 km altitude regime where there is a high concentration of debris already present [8]. In conclusion, the study states that while orbital debris mitigation measures like the "25-year rule" may "slow down the [orbital debris] population growth," they are ultimately "insufficient to constrain the Earth satellite population" [8]. Although its "no new launches" scenario is in no way realistic, the 2006 study provides clear evidence that the current 25-year rule has been insufficient for over a decade.

F. CONCLUSION

The most significant takeaway from the post-mission management of commercial satellites within the United States is the lack of active management and enforcement of post-mission activities as well as an adequate post-mission lifetime limit for decaying satellites. Current post-mission management processes significantly lack the appropriate mechanisms to enforce the post-mission plans approved in the pre-launch management segment. As a result, existing orbital debris concerns only continue to worsen. Adding to this concern is the inadequate lifetime limit for decaying satellites which remains fixed for linear growth in satellite population and not an exponential growth as we are currently seeing due to commercial satellite mega-constellations. Continuing with this lack of active management and enforcement will ultimately and negatively impact all space entities.

THIS PAGE INTENTIONALLY LEFT BLANK

V. RECOMMENDATIONS FOR MANAGEMENT FRAMEWORK

A. INTRODUCTION

Keeping with the intents of SPD-2 and SPD-3, the USG must balance ensuring sustainable and safe space operations alongside enabling the commercial space industry's growth when improving the management of commercial satellite mega-constellations. An imbalance between the two aims can either hamper the commercial space industry operating within a benign space environment or support a thriving commercial space industry operating within an extremely dangerous space environment. As the literature review discussed, the approach to managing commercial satellite mega-constellations, and all commercial satellites for that matter, should be soft governance. However, it is prudent to recognize that while the U.S. commercial space industry is "generally self-motivated" [41] in pursuing sustainable and safe space operations (good for business), hard governance may be occasionally necessary to ensure more direct responses for issues that require immediate action. Therefore, a practical balance of soft and hard governance with the aim of pursuing both sustainable and safe space operations as well as growth of the commercial space industry should be the framework from which future management improvements derive. To aid such efforts, the DOC's OSC should be the primary entity of focus. This chapter addresses the areas of concern previously discussed and offers improvements to the U.S. pre-launch, on-orbit, and post-mission management of commercial satellites with respect to commercial satellite mega-constellations.

B. PRE-LAUNCH MANAGEMENT

The U.S. pre-launch management of commercial satellites focuses primarily on satellite launch, communications, remote sensing, and, more recently, debris mitigation. Although these areas have relatively ensured safe and efficient satellite operations thus far, the increasing numbers of commercial satellites and mega-constellations now require the pre-launch management framework to incorporate minimum features of satellite safety.

1. Implement Core Safety Minimums

To aid on-orbit management efforts and improve the long-term sustainability and safety of operations in LEO, the USG should employ the OSC in implementing "core safety minimums," which can initially comprise minimum thresholds for satellite size, trackability, and maneuverability. As an entity designed for civil/commercial SSA and STM, the OSC would naturally have the most current and comprehensive knowledge of necessary requirements consistent with developments in SSA and STM capabilities. Much like the safety requirements for vehicles (e.g., seatbelts, airbags, and headlights) before being roadworthy, core safety minimums for satellites should similarly apply before launch. Regarding satellite size, a minimum diameter of 10 cm can be a value for the OSC to begin with due to the fact that the U.S. SSN currently and largely tracks objects of at least 10 cm in diameter [62]. Although a minimum satellite size could better aid U.S. SSA systems with tracking future satellites, the constraint could negatively impact the commercial satellite industry as operators pursue smaller-sized designs [27]. Since the objective of a minimum satellite size is to better ensure that future satellites are trackable, an option could be to simply circumvent a minimum satellite size and only implement a minimum threshold for satellite trackability.

For satellite trackability, active or passive means of cooperative identification and tracking can improve observation quality and observation frequency, which reduces orbit uncertainty [131]. Minimum thresholds for active satellite trackability can be systems such as LEDs and GPS or RF transponders [2], [10], [106]. Among these systems, RF transponders are "one of the most promising" and are already being integrated into new satellites, which "allow [s] very high accuracy tracking" to the extent of enabling RPO activities [2]. However, commercial satellite operators may not wholly support active systems for satellite trackability because of the financial, size, and mass costs to integrate active systems. As such, the OSC should begin with minimum thresholds for passive satellite trackability, such as corner reflectors or retro-reflectors [106], [131]. Passive systems of satellite trackability can accommodate radar, laser, and electro-optical tracking sensors [106], [131] and may be cheaper as well as lighter alternatives to active systems. In any case, the OSC should consider a minimum threshold of satellite trackability as part of the core safety minimums since improved on-orbit tracking contributes to the reduction of "false alarms" for conjunction assessments and further enables the identification of "truly dangerous conjunctions" [131].

In addition to a minimum threshold for satellite trackability, the OSC should consider a minimum threshold for satellite maneuverability as another element of the core safety minimums. Ensuring the maneuverability of all future satellites can enable on-orbit management entities and processes to better mitigate and prevent conjunctions or collisions. Although commercial satellite operators may not invite the additional weight of an onboard propulsion system, especially those operating SmallSats in lower altitudes of LEO, there is now little room for error caused by non-maneuvering satellites. The current number of the orbital debris population, approximately 100.5 million [35] including lethal nontrackable (LNT) and large derelict objects [134], highlights the need for satellite maneuverability to enable collision avoidance and ensure satellites are not forms of debris themselves. Even satellites in lower LEO altitudes that intend to leverage atmospheric drag and therefore do not possess onboard propulsion [57] are at risk of conjunctions and collisions as there is potential for "high and sustained collision rates at altitudes below 700 km" caused by the high density of decaying objects [39]. While all satellites should be capable of maneuvering, it may not be feasible for many smaller-sized satellites to possess onboard propulsive capabilities due to size or mass constraints. Therefore, satellites above a specific altitude should possess onboard propulsive capabilities and, if unable, should remain below the specified altitude. The SSC recommends that all satellites above 400 km should possess onboard propulsive capabilities [107] as satellites at or below 400 km could de-orbit within a year [136]. The OSC should begin with the SSC's recommended altitude of 400 km as a threshold for requiring commercial satellites to possess maneuver capability.

While the core safety minimums can initially comprise thresholds for satellite trackability and maneuverability, future iterations could include other dimensions of satellite design if necessary. With this said, however, it is critical that the OSC collaborates with the commercial satellite industry in the development of core safety minimums to implement practical requirements that support the long-term sustainability and safety of satellite operations as well as the growth of the satellite industry. As these proposed pre-launch management requirements imply, the implementation of the core safety minimums is hard governance.

C. ON-ORBIT MANAGEMENT

The U.S. on-orbit management of commercial satellites lacks a governing presence. To effectively facilitate management of significantly larger numbers of active satellites, the on-orbit management framework must evolve to incorporate clearly defined rules that manage day-to-day satellite operations, a common base of core on-orbit management definitions, and a national entity for commercial SSA and STM.

1. Establish Rules for Day-to-Day Satellite Operations

The establishment of a "rules of the road" concept in space, much like those observed and exercised in today's motorways, airways, and waterways, is critical for ensuring sustainable and safe space operations. While rules for day-to-day satellite operations should apply to all orbital regimes, this section intentionally focuses on LEO as it is the regime in which most commercial satellite mega-constellations have deployed or will deploy. Furthermore, while such rules should address a broad variety of space activities and events, this section focuses on conjunction and collision avoidance between two maneuverable objects to provide initial groundwork for future expansion.

The large majority of current and planned commercial satellite mega-constellations possess missions for remote sensing or communications [9], [11]. Due the fact that these missions require satellites, even those not tied to constellations, to maintain a "fixed angle about nadir for imaging or maintain beam lay-down patterns" [107], a set of rules for day-to-day satellite operations that mitigates or prevents conjunctions and collisions should avoid interfering with mission operations (e.g., "non-zero yaws" [107]). Since many of today's LEO satellites with maneuver capability can perform basic maneuvers to overcome the effects of drag (e.g., positive in-track delta-V), the initial set of rules for day-to-day satellite operations should leverage this relatively common satellite capability to take advantage of "semimajor axis or orbital period changes" as they offer effective means of lowering conjunction and collision risk by phasing time [107].

For instance, satellites at an operational altitude of 780 km can create "~135 meters/ day of along-track change" with a single meter adjustment in semimajor axis [107]. Although a simple method, this approach is not only effective in "increasing separation from another object for most conjunctions," [107] but also accommodates the majority of current and future LEO satellites and constellations. As for thresholds of sufficient mitigation or prevention, the initial set of rules for day-to-day satellite operations should reference an agreement established among OneWeb, Maxar, and Iridium, which suggests that "each satellite should maneuver by a magnitude that mitigates the conjunction to [a Pc of] less than [1x10^-6]" [107]. Although the safety threshold applies to conjunctions involving two maneuverable satellites, it can also apply to conjunctions involving a maneuverable satellite and a non-maneuvering object (e.g., unresponsive active satellite or orbital debris). However, a question that remains is how satellites involved in a conjunction should maneuver. This is a critical point to clarify to "avoid both objects executing maneuvers that nullify each other" [107]. Furthermore, there are significant variables to consider such as whether or not the satellites have positive, negative, or both in-track maneuver capabilities, which limit or enable maneuver options. As such, the initial set of rules for day-to-day satellite operations will require a system that designates which of the two satellites involved in a conjunction should maneuver and when.

Therefore, the USG should employ the OSC to establish the first set of space traffic rules that leverage the most basic propulsive capability (i.e., positive in-track delta-V) and establish a designation system that identifies which of the two satellites involved in a conjunction executes a maneuver and when. Although an ideal start to space traffic rules would be a system that leverages both positive and negative in-track maneuvers, not all LEO satellites currently possess retrograde thrusters [107]. Regarding a system for designating the maneuvering satellite, the process can be based on a variety of satellite values, such as available fuel, catalog number, size, or mass, among others. Moving forward in this approach, the OSC should collaborate with the commercial satellite industry to develop and fine-tune the rules for day-to-day satellite operations. To this effort, the OSC should also require commercial satellite operators to share vital information such as tracking data, satellite ephemeris, maneuver plans, thruster capabilities, fuel estimates, and contact information [107], which can aid decision processes for rules of day-to-day satellite operations.

2. Establish Core Definitions and Standards

The absence of common core definitions and standards for on-orbit management activities such as SSA and STM can be damaging to future developments or operations in the management of commercial satellite mega-constellations. Although SPD-3 defines SSA and STM, the document does not describe "decision-making and maneuvering processes" [57] nor does it define other terms relevant to on-orbit management (e.g., conjunction and conjunction assessment, among others). To prevent misinterpretation and false assumptions among satellite operators when conducting constructive or even time-sensitive dialogue, the on-orbit management framework should call on the OSC to explicitly define standard thresholds and describe the basic elements that comprise core on-orbit management terms. To the best extent possible, standards, procedures, and thresholds should accompany the description of the object, event, or process to avoid ambiguity. For instance, a conjunction should be defined as "an unsafe local minimum separation distance between the positional components of two trajectories where the probability of collision is greater than 1x10^-6" [107], [123]. Additionally, the establishment of common standards and procedures (e.g., force models, propagation tools, and OD algorithms) can further avoid ambiguity. The OSC should also define more on-orbit management terms, even those that may seem trivial, such as catalog, risk, and screening, which can all easily vary in meaning as they incorporate different levels of detail, accuracy, and capability. With significantly more objects expected to exist in LEO, there is potential for a reduction in effective mitigation or prevention timelines. As such, it is critical for all U.S. satellite operators to be on the same page especially when using basic on-orbit management terminology.

3. Establish and Empower National Entity for SSA/STM

The absence of dedicated national entities for commercial SSA and STM prevents effective management of current and future commercial satellite mega-constellations. Although SPD-3 directed the DOC to take on civil/commercial SSA and STM responsibilities from the USAF/USSF, the OSC remains unsupported by Congressional acts [104]. With the increasing pace of space operations largely in part due to commercial satellite mega-constellations, the on-orbit management framework will require the OSC to possess sufficient funding, resources, and legal authorities. Therefore, Congress must advance the stagnant transition of civil/commercial SSA and STM responsibilities to the OSC and empower the OSC with funding, resources, and legal authorities. Without such support to the OSC, the USG will be unable to ensure “a good position to maintain safe space operations” [104].

Regarding SSA, Congress must transform the OSC into the Bureau of Space Commerce [127]. In addition, the OSC must receive adequate and non-fungible funding that supports its national SSA responsibilities and services such as the continued development of the Open Architecture Data Repository (OADR)—a single object catalog concept that “improve [s] SSA data interoperability and enable [s] greater SSA data sharing” [137]. The concept of a single national object catalog can reduce strain on maintenance and assessments since “[o]nly one SSA analysis is required against that single catalog, and all resources are devoted to maintaining that single catalog at the highest achievable accuracy” [138]. Furthermore, commercial satellite operators utilizing the OADR should be more in sync due to the fact that a single catalog produces only “one version of generated SSA results” [138]. This can be especially helpful as commercial satellite mega-constellations raise the dynamic of the space operating environment through increasing numbers of active satellites, satellite operators, and on-orbit activities.

As such, the Congress must ensure that the OSC has sufficient funding and resources to “ingest and fuse/amalgamate space data contributions provided by any/all space trackers and satellite operators” [138] to decrease uncertainties in CA development and further reduce the need for unnecessary maneuvers. Moreover, this reiterates the need for the OSC to require satellite operators to share tracking data, satellite ephemeris, maneuver plans, thruster capabilities, fuel estimates, and contact information [107]. With this information, the OSC should provide improved modeling, tracking, and determinations for maneuvers which directly support commercial satellite operations at minimal expense for commercial satellite operators. While this is by no means an easy task, an initial starting point for the OSC should be collaborating and consulting with premiere U.S. commercial SSA entities such as LeoLabs, ExoAnalytic Solutions, and Analytical Graphics, Inc. (AGI), among others.

Regarding STM, Congress must draft and pass legislation to empower the OSC to function as a central directing authority. However, this does not suggest that the OSC should be responsible for the constant provision of direction for satellite traffic. Instead, the OSC should verify if satellite maneuver decisions by commercial operators are safe, recommend safe satellite maneuvers for planning purposes (if requested), authoritatively prohibit unsafe satellite maneuvers based on established Pc thresholds, and authoritatively direct satellites as hazardous events require. Although satellite operators should remain responsible for the safe maneuvering of their own satellites, the OSC can act as a verification and consultation mechanism for commercial STM as it would have access to the OADR and commercial tracking data. Furthermore, as the provision of CDMs to satellite operators is a critical element of STM, the OSC must establish a system that clearly outlines its responsibility for providing CDMs as well as operators' responsibility for verifying receipt of CDMs. This can ensure that all parties involved in a conjunction are aware of an imminent event and recognize the need for preventive action. Furthermore, as CDMs typically alert satellite operators of conjunctions "a few days to a week" in advance [104], the system can explicitly establish a timeline in which operators respond to CDMs which removes ambiguity and last-minute maneuvers due to unresponsive operators.

D. POST-MISSION MANAGEMENT

The U.S. post-mission management of commercial satellites lacks active supervision and enforcement of post-mission activities and implements an inadequate lifetime limit for satellites. As the surge of today's satellite launches due to commercial satellite mega-constellations inevitably leads to large numbers of de-orbiting satellites, the USG should incentivize operators to quickly de-orbit satellites at end-of-life.

1. Incentivize Post-mission Disposals

The active supervision and enforcement of PMD is challenging as the post-mission management of commercial satellites largely exists in the pre-launch management segment through satellite licensing requirements. Furthermore, current ambitions for active debris removal (ADR) remain in development and are, at the moment, “economically and technologically unfeasible” [139]. As the number of active satellites significantly increase due to commercial satellite mega-constellations, PMD compliance becomes more imperative. With limited options for actively supervising and enforcing PMD, the post-mission management framework should incentivize PMD as a near-term solution for ensuring compliance. Mirroring the point system for drivers on today’s roadways, the USG should establish a similar point system for satellite operators in space. Today, most states utilize a point system where drivers receive demerits based on violations of established traffic rules [140]. Within these point systems, a higher value of demerits corresponds to a higher chance of a driver’s license becoming suspended. Similarly, a point system should apply to satellite operators where violations of established space rules (e.g., PMD) could result in negative impacts such as higher pre-launch application fees, more stringent pre-launch assessments, or even suspension from launch operations (for repeating offenders). For obvious reasons, suspended operators would continue operating their satellite, but would have to remove their demerits through means like reviews and demonstrations of operational safety and compliance. Additionally, the AST requires satellite operators to possess a third-party liability insurance for launches. Similar to how vehicle insurers raise rates for accident-prone drivers, satellite insurers can do the same for negligent satellite operators.

Within this framework, the responsibility for active supervision and enforcement for PMD rests with satellite operators, as it should be. Since “accidents” in space are rather difficult to conceal, there is more of an incentive for satellite operators to execute their proposed PMD plans. Furthermore, the provision of truer incentives for responsible satellite operators should come through means such as reduced application fees or streamlined application processes. To begin implementing such a system, the USG should clearly establish the OSC as the entity for PMD enforcement. Moving forward, the OSC should collaborate and consult with well-established STM and debris mitigation entities such as the SSC and IADC to develop standards and thresholds from which a point system is based as well as the repercussions of negligent or unsafe behaviors.

2. Reduce Orbit Lifetime Limit of 25 Years

As studies now clearly suggest, the orbit lifetime of 25 years for decaying satellites is no longer adequate for ensuring the long-term sustainability and safety of space. Already, several operators of large satellite constellations "have realized that placing their satellites on 25-year decay orbits will still cause a substantial increase in the debris over the long term due to the large number of [involved] satellites, their mass, and the altitude regime they must transit to re-enter" [131]. With more active spacecraft operating in space due to commercial satellite mega-constellations, the USG must reduce the post-mission orbit lifetime for spacecraft to remove objects quicker from the congested operating environment. One option comes from Dr. Darren McKnight in *Space Traffic Management – Do Not Build on a Weak Foundation*: reduce the orbit lifetime limit of future satellites to 1 year [141]. Although the reduction is significant, it can substantially decrease the rate of collision in LEO, especially at lower altitudes where satellites decay, [141] and can appropriately facilitate the increasing pace at which satellites de-orbit.

However, one of the major arguments that oppose this approach is that a reduction contributes negligibly over a 200-year period [141]. For instance, some suggest that a reduction of post-mission satellite orbit lifetimes from 25 years to 5 years only contributes a 10% decrease in the number of objects (over 200 years) and is therefore statistically insignificant [141]. As McKnight asserts, however, the research used for the assertion "aggregates cataloged debris from all of LEO and, therefore, ignores debris created below ~800 km since debris at these altitudes washes out in decades" [141]. As a result, the assertion's research does not consider both the high number of "large breakups every few years below ~850 km" since they do not accumulate over a 200-year period [141], and the fact that this significantly affects access to space. Furthermore, the assertion's research utilizes a 200-year simulation, which although useful for assessing long-term sustainability, is inadequate for assessing safety as it disregards "commercially relevant altitudes" [141]. As such, the USG should reduce the post-mission satellite orbit lifetime limit from 25 years to 1 year to best prepare for the increasing pace of launch and de-orbit of satellites belonging to commercial mega-constellations. An updated USGODMSP should promulgate the reduction; the AST, FCC, and CRSRA should implement it in their pre-launch licensing requirements for debris mitigation; and the OSC should enforce it.

In addition, it is important to recognize that the limit of 25 years for post-mission orbit lifetime is based on a “typical propellant requirement” which requires 2–5% of the upper stage’s dry mass [141]. Due to the fact that remaining below a “5% mass fraction in satisfying a more stringent PMD threshold” may be too difficult for commercial satellite operators today (due to size, mass, and fuel constraints), commercial satellite operators could turn to electric propulsion [141]. As proven in a study by Aerojet Rocketdyne, advancements in electric thruster technology could effectively enable a significantly shorter post-mission orbit lifetime limit and allow satellites to remain “within the 5% mass fraction threshold” [141], as Figure 7 depicts. Therefore, USG should encourage the commercial space industry to utilize electric propulsion for PMD activities.

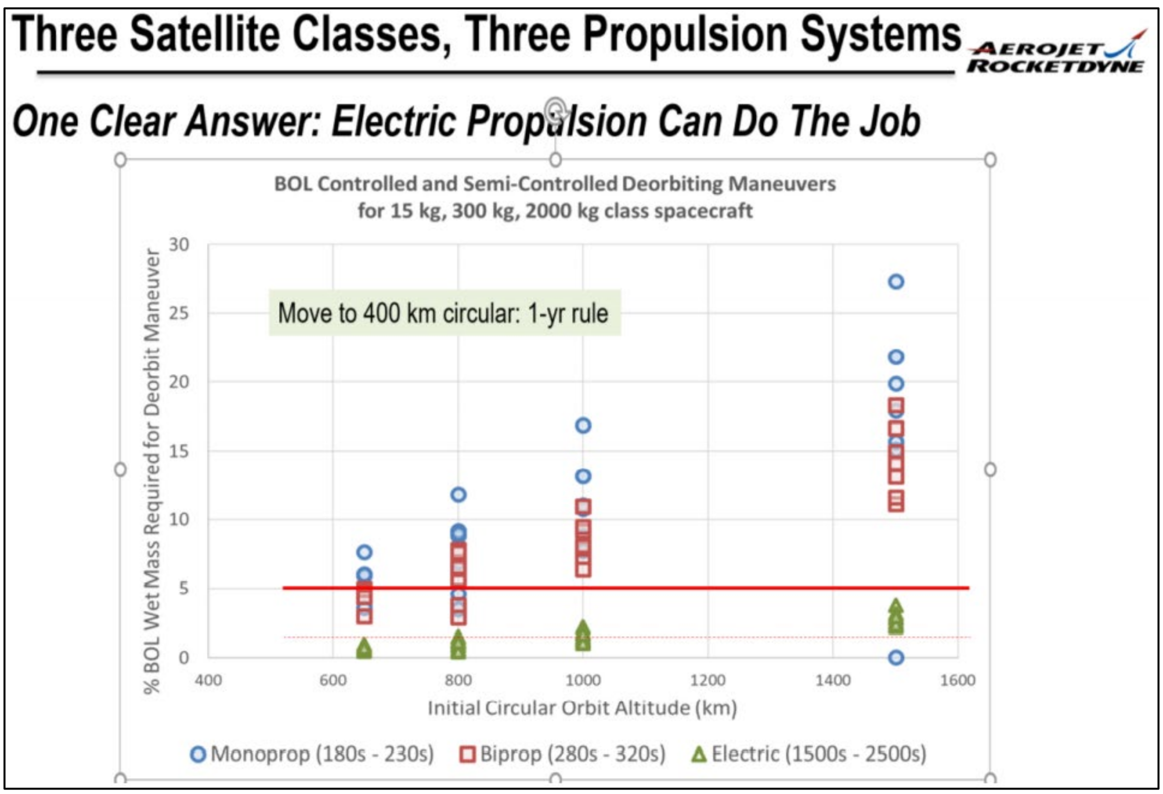

Figure 7. Comparison of Electric to Monoprop and Biprop Propulsion for PMD. Source: [141].

E. TRANSFERABLE MANAGEMENT FRAMEWORK

As space is inherently an international domain, improved management of commercial satellite mega-constellations cannot be exclusive to the United States. However, the international community, primarily government-to-government interaction, has historically proven to be slow in reaching consensus on requirements for space activities [40]. Therefore, it may be more effective to provide spacefaring nations with an example of a functioning management framework that employs a practical balance of soft and hard governance for enabling sustainable and safe space operations. A management framework that purely focuses on improving the sustainability and safety of space as well as growth of its own commercial space industry, is likely to be enticing for many, if not all, spacefaring nations. If widely adopted, there is potential for universal implementation of space guidelines, standards, and best practices that would have otherwise been unrealized through traditional means of international consensus. Furthermore, wider adoption by spacefaring nations eventually implies isolation for those not participating. This was the case in 2019 when Russia, after "continued veto of the 21 guidelines" established by COPUOS, agreed to the guidelines in fear of isolation [142]. As such, the USG should frame its improvements to the management of commercial satellite mega-constellations for straightforward adoption by other spacefaring nations regardless of economic or technologic standing. Improvements should not leverage or require excessive costs that only the United States can satisfy. Additionally, improvements should not solely leverage government proprietary SSA and STM capabilities. Instead, improvements should largely utilize commercial SSA and STM capabilities, which intrinsically offer services to a wider audience and can further enable adoption by other spacefaring nations.

One of the challenges of establishing such a management framework partly stems from the fear of appearing too stringent which might encourage the commercial satellite industry to do business elsewhere. Therefore, it is even more imperative for the United States to take the initiative and be the first to set an example. Considering that the United States is one of the most active spacefaring nations [143] and also the nation that possesses "the world's largest commercial satellite constellation" [4], it is best situated to establish and demonstrate an effective management framework that improves the sustainability and safety of space as well as growth of its own commercial space industry. To help accomplish this task, the USG should consider establishing a national consortium initially comprised of well-established commercial satellite operators.

The primary purpose of the national consortium should be continuously stimulating discussions pertaining to sustainability and safety concepts for satellite operations, and intentionally pursuing industry-wide guidelines, standards, and best practices for U.S. commercial satellites. Similar examples of such an entity include the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS), the Satellite Industry Association (SIA), and the SSC [41]. While the entity should one day act as a mediator between satellite operators and policymakers, proposing well-established consensus-based rules for hard governance, the initial objective of the entity should be promulgating and implementing widely accepted sustainability and safety concepts within the U.S. commercial space industry (soft governance exercised by the commercial industry itself). The mutual relationship between the USG and the proposed national consortium should better ensure that the U.S. management framework for commercial satellite mega-constellations is appealing and transferable to other spacefaring nations.

F. CONCLUSION

Moving forward, the USG must find a balance in protecting the space environment and assets therein as well as the freedom of the commercial space industry to conduct operations. As illustrated throughout this thesis, the collective challenge facing these goals is complex and multifaceted. Therefore, it is critical that the USG avoids improving only one dimension of commercial satellite and satellite mega-constellation management. Instead, the USG should consider improvements in all segments of management and should heavily leverage and utilize the knowledge, opinion, and capabilities of the commercial space industry. In broader terms, this chapter posits four significant takeaways for management improvements: (1) the USG should establish a management framework for improving the sustainability and safety of space as well as growth of the commercial space industry; (2) the USG should adopt soft governance rules that derive from widely-accepted guidelines, standards, and best practices of the commercial space industry; (3) the USG should apply hard governance rules to areas that require direct and immediate action; and (4) the USG must establish a management framework that straightforwardly transfers to other spacefaring nations.

VI. CONCLUSION

A. KEY POINTS AND RECOMMENDATIONS

This thesis presents the author's recommendations for how the USG should improve the management of commercial satellite mega-constellations to ensure the sustainability and safety of LEO as well as enable growth of the commercial space industry. This thesis examines entities, documents, and processes involved in the U.S. pre-launch, on-orbit, and post-mission managements of commercial satellites to identify areas of concern raised by commercial satellite mega-constellations. The main challenge facing the management of commercial satellite mega-constellations is the lack of national-level oversight and standards specifically for these "new space" massive architectures. As these large constellations involve more satellites and draw more satellite operators, the potential for accidents can grow significantly if left inappropriately managed. This fact is apparent in all three segments of commercial satellite management.

In the pre-launch management segment, entities and processes largely focus on launch, communications, remote sensing, and, more recently, orbital debris mitigation requirements. However, the rise of commercial satellite mega-constellations now necessitates pre-launch management entities and processes to incorporate minimum safety features for satellites that improve on-orbit safety (i.e., satellite maneuverability) and management activities (i.e., satellite trackability). Therefore, the USG should employ the OSC in implementing "core safety minimums" that include propulsive capabilities and passive or active means of trackability.

In the on-orbit management segment, there is a significant lack of a governing presence for commercial satellites. There remains an absence of rules for the day-to-day operations of satellites and a governing set of core definitions and standards for on-orbit management activities. Furthermore, there is an absence of dedicated, empowered, and authoritative entities for national SSA and STM. With the conservative expectation of a "ten- to twenty-fold increase in the number of orbiting active spacecraft within the next ten years alone" [41], commercial satellite mega-constellations necessitates on-orbit management protocols to address the looming interaction of satellites, operators, and risks. As such, the USG should employ the OSC to establish a basic body of space traffic rules and a set of core definitions and standards for on-orbit management activities. In addition, Congress must improve the formalization and empowerment of the OSC to enable it to effectively act as the nation's focal point for commercial SSA and STM.

In the post-mission management segment, there is a lack of active enforcement for post-mission activities and an adequate lifetime limit for decaying satellites. With the increasing pace at which commercial satellites launch (potentially 1,100 per year by 2025 [2]) and de-orbit as a result of commercial satellite mega-constellations, the USG should consider new alternatives for enforcing PMD and preventing collisions caused by decaying objects. Therefore, the USG should designate the OSC as the national entity for incentivizing PMD, perhaps through a point system, and should reduce the post-mission orbit lifetime limit from 25 years to 1 year.

In all three management segments, the USG/OSC must leverage and communicate with the commercial space industry, especially satellite operators, to better develop effective improvements to the management of commercial satellites and mega-constellations. The commercial space industry provides a wealth of knowledge, experience, and insight regarding space operations which will be significantly valuable for evaluating the feasibility of proposed improvements. Close coordination with the commercial space industry can better ensure that improvements are promulgated and implemented efficiently and effectively.

Lastly, improved management of commercial satellites and mega-constellations cannot be exclusive to the United States. Due to the fact that the international community remains unable to reach consensus on requirements for space activities, it may be more effective to provide the international community with a functioning management framework that pursues improving sustainable and safe space operations as well as growth of its commercial space industry. Such a management framework can likely be enticing for many, if not all, spacefaring nations to adopt. Therefore, the USG, as one of the world's leading nations in space, must take the initiative and ensure that improvements to its management framework is transferable to other spacefaring nations. This means keeping true to purely pursuing sustainable and safe space operations as well as growth of the commercial space industry. This also includes avoiding improvements that leverage or require excessive costs and technologies that only the United States can satisfy. Afterall, space is inherently an international domain where one accident affects all.

B. SUGGESTIONS FOR FUTURE RESEARCH

There are several areas for future research. One area that follows this research is the feasibility of other spacefaring nations adopting the improvements to commercial satellite management proposed in this thesis. Additional studies should examine requisite infrastructure, policy, and costs for implementing the proposed improvements. Regarding pre-launch management areas for future research, studies should explore the feasibility, requirements, and advantages or disadvantages of consolidating all satellite pre-launch management requirements in a single entity or process. If possible and implemented, the result could streamline the commercial satellite application process and reduce excess costs for both the USG and commercial satellite operators. Future on-orbit management studies should explore and define the technical details enabling the rules for day-to-day satellite operations (i.e., space "rules of the road") especially for when orbits become more complicated by new electric propulsion systems and orbits no longer fit standard propagation models. While the advantages of such a concept are apparent, feasibility is again a question that requires examination. Lastly, future research should explore and define the PMD point system proposed in this thesis and alternative incentive systems for post-mission management.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

[1] Y. Lu, Q. Shao, H. Yue, and F. Yang, "A review of the space environment effects on spacecraft in different orbits," *IEEE*, vol. 7, pp. 93473–93488, Jul. 2019, doi: 10.1109/ACCESS.2019.2927811.

[2] M. Dominguez, M. Faga, J. Fountain, P. Kennedy, and S. O'Keefe, "Space traffic management: assessment of the feasibility, expected effectiveness, and funding implications of a transfer of space traffic management functions," National Academy of Public Administration, Washington, DC, USA, 102252, Aug. 2020. [Online]. Available: https://s3.us-west-2.amazonaws.com/napa-2021/studies/united-states-department-of-commerce-office-of-space-commerce/NAPA_OSC_Final_Report.pdf

[3] B. Weeden, "Space situational aware. Examining key issues." *Chang. Landsc. Subcomm. Space Aeronaut.*, Accessed: Apr. 28, 2021. [Online]. Available: https://science.house.gov/imo/media/doc/Weeden%20Testimony.pdf

[4] C. Henry, "SpaceX becomes operator of world's largest commercial satellite constellation with Starlink launch," *Space News*, Jan. 06, 2020. https://spacenews.com/spacex-becomes-operator-of-worlds-largest-commercial-satellite-constellation-with-starlink-launch/

[5] J. Foust, "SpaceX continues Starlink deployment with latest launch," *Space News*, May 04, 2021. https://spacenews.com/spacex-continues-starlink-deployment-with-latest-launch/

[6] L. Wood, "Satellite constellation networks," in *Internetworking and Computing Over Satellite Networks*, Y. Zhang, Ed. Boston, MA, USA: Springer, 2003, pp. 13–34. doi: 10.1007/978-1-4615-0431-3_2.

[7] P. Wauthier, "The impact of small satellites on space situational awareness," *NewSpace International*, vol. 3, no. 3, pp. 16–20, Sep. 2020.

[8] J.-C. Liou and N. L. Johnson, "Instability of the present LEO satellite populations," *Adv. Space Res.*, vol. 41, no. 7, pp. 1046–1053, Jan. 2008, doi: 10.1016/j.asr.2007.04.081.

[9] P. Chrystal, D. McKnight, and P. L. Meredith, "New space, new dimensions, new challenges: how satellite constellations impact space risk," *Swiss Re Corporate Solutions Ltd*, Jul. 17, 2018. [Online]. Available: https://www.swissre.com/Library/how-satellite-constellations-impact-space-risk.html

[10] T. J. Muelhaupt, M. E. Sorge, M. Jamie, and R. S. Wilson, "Space traffic management in the new space era," *J. Space Saf. Eng.*, vol. 6, no. 2, pp. 80–87, Jun. 2019, doi: 10.1016/j.jsse.2019.05.007.

[11] M. A. Hallex and T. S. Cottom, "Proliferated commercial satellite constellations: implications for national security," *Jt. Force Q.*, vol. 2nd Quarter, no. 97, pp. 20–29, Apr. 2020.

[12] T. Highfill, P. Georgi, and D. Dubria, "Measuring the value of the U.S. space economy," *J. U.S. Bur. Econ. Anal.*, vol. 99, no. 12, Dec. 2019, [Online]. Available: https://apps.bea.gov/scb/2019/12-december/pdf/1219-commercial-space.pdf

[13] Space Foundation, "Global space economy grows in 2019 to $423.8 billion, the Space Report 2020 Q2 analysis shows," Jul. 30, 2020. https://www.spacefoundation.org/2020/07/30/global-space-economy-grows-in-2019-to-423-8-billion-the-space-report-2020-q2-analysis-shows/

[14] Space Foundation, "The space report 2010 reveals global space economy grew 40 percent over five years," Apr. 12, 2010. https://www.spacefoundation.org/2010/04/12/the-space-report-2010-reveals-global-space-economy-grew-40-percent-over-five-years/

[15] Space Foundation, "The space report 2011 is now available," May 2011. https://www.spacefoundation.org/2011/05/02/the-space-report-2011-is-now-available/

[16] Space Foundation, "Space Foundation's 2012 report reveals 12.2 percent global space industry growth in 2011," Apr. 05, 2012. https://www.spacefoundation.org/2012/04/05/space-foundations-2012-report-reveals-12-2-percent-global-space-industry-growth-in-2011/

[17] Space Foundation, "Space Foundation's 2013 report reveals 6.7 percent growth in the global space economy in 2012," Apr. 02, 2013. https://www.spacefoundation.org/2013/04/02/space-foundations-2013-report-reveals-6-7-percent-growth-in-the-global-space-economy-in-2012/

[18] Space Foundation, "The Space Report 2014 is now available; provides definitive perspective on the 2013 global space industry," Jun. 2014. https://www.spacefoundation.org/2014/06/02/the-space-report-2014-is-now-available-provides-definitive-perspective-on-the-2013-global-space-industry/

[19] Space Foundation, "The Space Report 2015 PDF is now available." https://www.spacefoundation.org/2015/07/18/the-space-report-2015-pdf-is-now-available/ (accessed Apr. 28, 2021).

[20] Space Foundation, "Find global space facts in the Space Report 2016," Aug. 2016. https://www.spacefoundation.org/2016/07/29/find-global-space-facts-in-the-space-report-2016/

[21] Space Foundation, "Space Foundation report reveals global space economy at $329 billion in 2016," Aug. 03, 2017. https://www.spacefoundation.org/2017/08/03/space-foundation-report-reveals-global-space-economy-at-329-billion-in-2016/

[22] Space Foundation, "Space Foundation report reveals global space economy at $383.5 billion in 2017," Jul. 19, 2018. https://www.spacefoundation.org/2018/07/19/space-foundation-report-reveals-global-space-economy-at-383-5-billion-in-2017/

[23] Space Policy Online, "Commercial space activities," *Space Policy Online*, Jan. 27, 2021. https://spacepolicyonline.com/topics/commercial-space-activities/

[24] National Aeronautics and Space Administration, "Global Positioning System history," Aug. 07, 2017. https://www.nasa.gov/directorates/heo/scan/communications/policy/GPS_History.html

[25] Aerospace Corporation, "Brief history of GPS," Feb. 02, 2021. https://aerospace.org/article/brief-history-gps

[26] A. L. Allison, "WRC-19: New space law enabling the sustainability of LEO," presented at the World Radiocommunication Conference 2019, Sharm el-Sheikh, Egypt, Nov. 2019. [Online]. Available: https://amostech.com/TechnicalPapers/2020/SSA-SDA/Allison.pdf

[27] A. K. King, "Small satellite boom poses challenges for regulators," Congressional Research Service, Washington, DC, USA, IF11382, Jan. 2020. [Online]. Available: https://fas.org/sgp/crs/space/IF11382.pdf

[28] International Telecommunication Union, *Measuring Digital Development: Facts and Figures: 2019*. Geneva, Switzerland: International Telecommunication Union, 2019. Accessed: Apr. 28, 2021. [Online]. Available: https://www.itu.int/en/ITU-D/Statistics/Documents/facts/FactsFigures2019_r1.pdf

[29] Federal Communications Commission, "Broadband progress report: Significant improvements but digital divide persists," Federal Communications Commission, Washington, DC, USA, FCC 16–006, Jan. 2016. Accessed: Apr. 28, 2021. [Online]. Available: https://docs.fcc.gov/public/attachments/DOC-337471A1.pdf

[30] B. P. Hardy, "Long-term effects of satellite megaconstellations on the debris environment in low Earth orbit," M.S. thesis, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA, 2020. [Online]. Available: http://hdl.handle.net/2142/108004

[31] C. Henry, "Space insurer Swiss Re leaves market," *SpaceNews*, Aug. 01, 2019. https://spacenews.com/space-insurer-swiss-re-leaves-market/ (accessed May 03, 2021).

[32] Morgan Stanley, "Space economy: the new global space age," Feb. 17, 2021. https://www.morganstanley.com/Themes/global-space-economy

[33] Inter-Agency Space Debris Coordination Committee, "IADC Space Debris Mitigation Guidelines," Inter-Agency Space Debris Coordination Committee, IADC-02-01, Mar. 2020. [Online]. Available: https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf

[34] Union of Concerned Scientists, "Historical growth of space debris," May 18, 2009. Accessed: May 03, 2021. [Online]. Available: https://www.ucsusa.org/sites/default/files/2019-10/Debris-growth-graph-5-18-09.ppt

[35] J.-C. Liou, "Risk from orbital debris," presented at the Brookings Institution, Washington, DC, USA, May 13, 2020. Accessed: May 03, 2021. [Online]. Available: https://www.brookings.edu/wp-content/uploads/2020/05/Space-Junk-PPT_J.C.-Liou_5.13.20.pdf

[36] B. Weeden, "2007 Chinese anti-satellite test fact sheet," Secure World Foundation, Nov. 2010. [Online]. Available: https://swfound.org/media/9550/chinese_asat_fact_sheet_updated_2012.pdf

[37] P. D. Anz-Meador, J. N. Opiela, D. Shoots, and J.-C. Liou, "History of on-orbit satellite fragmentations, 15th edition," National Aeronautics and Space Administration (NASA), Lyndon B. Johnson Space Center, Houston, TX, USA, NASA/TM-2018-220037, Nov. 2018. [Online]. Available: https://www.orbitaldebris.jsc.nasa.gov/library/20180008451.pdf

[38] B. Weeden, "2009 Iridium-Cosmos collision fact sheet," Secure World Foundation, Nov. 2010. Accessed: May 03, 2021. [Online]. Available: https://swfound.org/media/6575/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf

[39] H. G. Lewis, "Understanding long-term orbital debris population dynamics," *J. Space Saf. Eng.*, vol. 7, no. 3, pp. 164–170, Sep. 2020, doi: 10.1016/j.jsse.2020.06.006.

[40] J. C. Moltz, *Crowded Orbits: Conflict and Cooperation in Space*. New York, USA: Columbia Press University, 2014.

[41] D. L. Oltrogge and I. A. Christensen, "Space governance in the new space era," *J. Space Saf. Eng.*, vol. 7, no. 3, pp. 432–438, Sep. 2020, doi: 10.1016/j.jsse.2020.06.003.

[42] D. McKnight, "A practical perspective on Space Traffic Management," *J. Space Saf. Eng.*, vol. 6, no. 2, pp. 101–107, Jun. 2019, doi: 10.1016/j.jsse.2019.03.001.

[43] M. P. Gleason, "Establishing space traffic management standards, guidelines and best practices," *J. Space Saf. Eng.*, vol. 7, no. 3, pp. 426–431, Sep. 2020, doi: 10.1016/j.jsse.2020.06.005.

[44] J. N. Pelton, "A path forward to better space security: Finding new solutions to space debris, space situational awareness and space traffic management," *J. Space Saf. Eng.*, vol. 6, no. 2, pp. 92–100, Jun. 2019, doi: 10.1016/j.jsse.2019.04.005.

[45] E. S. Nightingale, B. Lal, B. C. Weeden, A. J. Picard, and A. R. Eisenstadt, "Evaluating options for civil space situational awareness (SSA)," Institute for Defense Analyses, Washington, DC, USA, P-8038, Aug. 2016. [Online]. Available: https://www.ida.org/-/media/feature/publications/e/ev/evaluating-options-for-civil-space-situational-awareness-ssa/p-8038.ashx

[46] United Nations Office for Outer Space Affairs, "Committee on the Peaceful Uses of Outer Space." https://www.unoosa.org/oosa/en/ourwork/copuos/index.html (accessed May 03, 2021).

[47] United Nations Office for Outer Space Affairs, "Treaty on the principles governing the activities of states in the exploration and use of outer space, including the moon and other celestial bodies," Dec. 1966. [Online]. Available: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html

[48] United Nations Office for Outer Space Affairs, "Convention on registration of objects launched into outer space," Nov. 1974. [Online]. Available: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/registration-convention.html

[49] United Nations Office for Outer Space Affairs, "Members of the Committee on the Peaceful Uses of Outer Space." https://www.unoosa.org/oosa/en/members/index.html (accessed May 04, 2021).

[50] International Telecommunication Union, "Historical highlights: ITU and radiocommunication." https://www.itu.int/en/history/Pages/FocusOnRadiocommunication.aspx (accessed May 04, 2021).

[51] International Telecommunication Union, *Collection of the Basic Texts Adopted by the Plenipotentiary Conference*. Geneva, Switzerland: International Telecommunication Union, 2019. [Online]. Available: http://search.itu.int/history/HistoryDigitalCollectionDocLibrary/5.22.61.en.100.pdf

[52] International Telecommunication Union, “Sharing the sky—ITU’s role in managing satellite and orbit spectrum resources,” 2014. Accessed: May 04, 2021. [Online]. Available: https://www.itu.int/en/plenipotentiary/2014/newsroom/Documents/backgrounders/pp14-backgrounder-sharing-the-sky.pdf

[53] International Telecommunication Union, “Welcome to ITU-R,” 2021. https://www.itu.int/en/ITU-R/information/Pages/default.aspx (accessed May 04, 2021).

[54] International Telecommunication Union, “Mission statement,” 2021. https://www.itu.int/en/ITU-R/information/Pages/mission-statement.aspx (accessed May 04, 2021).

[55] N. Johnson, “Origin of the Inter-Agency Space Debris Coordination Committee,” pp. 70–71. [Online]. Available: https://ntrs.nasa.gov/api/citations/20150003818/downloads/20150003818.pdf

[56] Inter-Agency Space Debris Coordination Committee, “What’s IADC.” https://www.iadc-home.org/what_iadc (accessed May 04, 2021).

[57] B. Lal, A. Balakrishnan, B. M. Caldwell, R. S. Buenconsejo, and S. A. Carioscia, “Global trends in space situational awareness (SSA) and space traffic management (STM),” Institute for Defense Analyses, Alexandria, VA, D-9074, Apr. 2018. [Online]. Available: https://www.ida.org/-/media/feature/publications/g/gl/global-trends-in-space-situational-awareness-ssa-and-space-traffic-management-stm/d-9074.ashx

[58] Space Safety Coalition, “Best practices for the sustainability of space operations.” https://spacesafety.org/ (accessed May 04, 2021).

[59] Space Safety Coalition, “Endorsees,” 2020. https://spacesafety.org/endorsees/ (accessed May 04, 2021).

[60] Federal Aviation Administration, “About the Office of Commercial Space Transportation,” Apr. 05, 2021. https://www.faa.gov/about/office_org/headquarters_offices/ast/

[61] National Archives, “Executive Order 12465—Commercial Expendable Launch Vehicle Activities,” Aug. 15, 2016. https://www.archives.gov/federal-register/codification/executive-order/12465.html

[62] D. Morgan, “Commercial space: federal regulation, oversight, and utilization,” Congressional Research Service, Washington, DC, R45416, Nov. 2018. [Online]. Available: https://fas.org/sgp/crs/space/R45416.pdf

[63] Federal Communications Commission, “International Bureau Satellite Division.” https://www.fcc.gov/general/international-bureau-satellite-division (accessed May 04, 2021).

[64] National Environmental Satellite Data and Information Service, “About the licensing of private remote sensing space systems,” Sep. 30, 2020. https://www.nesdis.noaa.gov/CRSRA/licenseHome.html

[65] *Land Remote Sensing Policy Act of 1992*. 1992. Accessed: May 04, 2021. [Online]. Available: https://www.congress.gov/bill/102nd-congress/house-bill/6133

[66] United States Department of State, “About us.” https://www.state.gov/about-us-office-of-space-affairs/ (accessed May 04, 2021).

[67] D. L. Oltrogge and S. Alfano, “The technical challenges of better space situational awareness and space traffic management,” *J. Space Saf. Eng.*, vol. 6, no. 2, pp. 72–79, Jun. 2019, doi: 10.1016/j.jsse.2019.05.004.

[68] United Nations Office for Outer Space Affairs, “Status of international agreements relating to activities in outer space as of 1 January 2020,” Jan. 2020. [Online]. Available: https://www.unoosa.org/documents/pdf/spacelaw/treatystatus/TreatiesStatus-2020E.pdf

[69] United Nations Office for Outer Space Affairs, “Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies,” Dec. 1966. [Online]. Available: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html

[70] United Nations Office for Outer Space Affairs, “Convention on registration of objects launched into outer space.” https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introregistration-convention.html (accessed May 04, 2021).

[71] Committee on the Peaceful Uses of Outer Space, “Report of the Committee on the Peaceful Uses of Outer Space,” New York, A/74/20, Jun. 2019. Accessed: May 04, 2021. [Online]. Available: https://www.unoosa.org/res/oosadoc/data/documents/2019/a/a7420_0_html/V1906077.pdf

[72] P. Martinez, “The UN COPUOS guidelines for the long-term sustainability of outer space activities,” Secure World Foundation, Nov. 2019. [Online]. Available: https://swfound.org/media/206891/swf_un_copuos_lts_guidelines_fact_sheet_november-2019-1.pdf

[73] International Telecommunication Union, “ITU publications: Radiocommunication (ITU-R),” 2021. [Online]. Available: https://www.itu.int/en/publications/ITU-R/Pages/default.aspx (accessed May 04, 2021).

[74] International Telecommunication Union, “Radio Regulations 2020,” 2020. [Online]. Available: https://www.itu.int/en/myitu/Publications/2020/09/02/14/23/Radio-Regulations-2020 (accessed May 04, 2021).

[75] Y. Takeuchi, “Legal aspects of international regime for space traffic management,” M.L. thesis, Institute of Air and Space Law, McGill University, Montreal, Canada, 2014. [Online]. Available: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiuv4mcmbHwAhXZJTQIHbZqAGYQFjAAegQIBBAD&url=https%3A%2F%2Fescholarship.mcgill.ca%2Fdownloads%2Fht24wn32m.pdf&usg=AOvVaw33ALn3P2SnGYJxppK865mY

[76] United Nations Office for Outer Space Affairs, “Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space,” Vienna, 2010. [Online]. Available: https://www.unoosa.org/pdf/publications/st_space_49E.pdf

[77] Space Safety Coalition, “Best Practices for the Sustainability of Space Operations,” Dec. 2019. [Online]. Available: https://spacesafety.org/wp-content/uploads/2021/04/Endorsement-of-Best-Practices-for-Sustainability_v40.pdf

[78] United States Government, “U.S. government orbital debris mitigation standard practices,” Nov. 2019. [Online]. Available: https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf

[79] J. Foust, “U.S. government updates orbital debris mitigation guidelines,” *SpaceNews*, Dec. 09, 2019. [Online]. Available: https://spacenews.com/u-s-government-updates-orbital-debris-mitigation-guidelines/

[80] M. Sorge, “Commercial space activity and its impact on U.S. space debris regulatory structure,” *Aerosp. Corp.*, p. 7, Aug. 2017.

[81] GovTrack, “Summary of H.R. 3942 (98th): Commercial Space Launch Act,” Oct. 11, 2018. https://www.govtrack.us/congress/bills/98/hr3942/summary

[82] B. Canis, “Changes in the U.S. commercial space industry,” Congressional Research Service, Washington, DC, IF10415, Jun. 2016. [Online]. Available: https://crsreports.congress.gov/product/pdf/IF/IF10415

[83] *Code of Federal Regulations Title 14 Chapter III*. [Online]. Available: https://www.ecfr.gov/cgi-bin/text-idx?SID=c07e47de2c393340dd020bcbbc87c644&mc=true&tpl=/ecfrbrowse/Title14/14cfr450_main_02.tpl

[84] R. Gobetz and K. Rogers, “Communications Act of 1934,” *Britannica*, Jun. 12, 2020. https://www.britannica.com/event/Communications-Act-of-1934

[85] *Code of Federal Regulations Title 47 Chapter I*. [Online]. Available: https://www.ecfr.gov/cgi-bin/text-idx?SID=11ac2d2131b251052ba6a838c873e1ba&mc=true&tpl=/ecfrbrowse/Title47/47chapterI.tpl

[86] *Code of Federal Regulations Title 15 Chapter IX Part 960*. [Online]. Available: https://www.ecfr.gov/cgi-bin/text-idx?SID=dfd33b74f46bb93a0a68fa1bd82721de&mc=true&node=pt15.3.960&rgn=div5

[87] Space Foundation, "Space Policy Directives (SPDs)," 2021. [Online]. Available: https://www.spacefoundation.org/space_brief/space-policy-directives/ (accessed May 04, 2021).

[88] Federal Aviation Administration, "Part 450: streamlining of launch and reentry licensing requirements," Mar. 11, 2021. https://www.faa.gov/space/streamlined_licensing_process/

[89] M. Davila, "New regulations on the licensing of private remote sensing space systems," *LMI Advisors*. https://www.lmiadvisors.com/new-regulations-on-the-licensing-of-private-remote-sensing-space-systems/ (accessed May 04, 2021).

[90] *Licensing of Private Remote Sensing Space Systems*. 2020. Accessed: May 04, 2021. [Online]. Available: https://www.federalregister.gov/documents/2020/05/20/2020-10703/licensing-of-private-remote-sensing-space-systems

[91] *Commercial Space Launch Act*. 1984. [Online]. Available: https://www.congress.gov/bill/98th-congress/house-bill/3942/text

[92] Cornell Law School, "51 U.S. Code § 50914 - Liability insurance and financial responsibility requirements." https://www.law.cornell.edu/uscode/text/51/50914 (accessed May 04, 2021).

[93] *Streamlined Launch and Reentry License Requirements*. 2021. [Online]. Available: https://www.federalregister.gov/documents/2020/12/10/2020-22042/streamlined-launch-and-reentry-license-requirements

[94] *Mitigation of Orbital Debris in the New Space Age*. 2020. [Online]. Available: https://www.federalregister.gov/documents/2020/08/25/2020-13185/mitigation-of-orbital-debris-in-the-new-space-age

[95] National Aeronautics and Space Administration, "About the Hubble space telescope," Dec. 18, 2018. https://www.nasa.gov/mission_pages/hubble/story/index.html

[96] National Aeronautics and Space Administration, "What are SmallSats and CubeSats?," Feb. 26, 2015. https://www.nasa.gov/content/what-are-smallsats-and-cubesats/

[97] International Telecommunication Union, "Characteristics, definitions and spectrum requirements of nanosatellites and picosatellites, as well as systems composed of such satellites," Geneva, SA.2312-0, Sep. 2014. [Online]. Available: https://www.itu.int/en/ITU-R/space/Documents/R-REP-SA.2312-2014-PDF-E.pdf

[98] M. Wall, "Tiny chipsats, big success: cracker-size probes phone home from orbit | space," *Space*, Jun. 04, 2019. [Online]. Available: https://www.space.com/tiny-chipsats-ace-demonstration-mission.html

[99] S. Erwin, "Space fence surveillance radar site declared operational," *SpaceNews*, Mar. 28, 2020. [Online]. Available: https://spacenews.com/space-fence-surveillance-radar-site-declared-operational/

[100] Lockheed Martin, "Space Fence." [Online]. Available:https://www.lockheedmartin.com/en-us/products/space-fence.html (accessed Apr. 27, 2021).

[101] J. L. Gonzalo, C. Colombo, and P. Di Lizia, "Analytical framework for space debris collision avoidance maneuver design," *J. Guid. Control Dyn.*, vol. 44, no. 3, pp. 469–487, Mar. 2021, doi: 10.2514/1.G005398.

[102] LeoLabs, "Space domain awareness: securing the new space race." [Online]. Available: https://www.leolabs.space/space-domain-awareness/ (accessed Apr. 27, 2021).

[103] D. Werner, "Leolabs declares Costa Rica Space Radar operational," *SpaceNews*, Apr. 22, 2021. [Online]. Available: https://spacenews.com/leolabs-declares-costa-rica-space-radar-operational/

[104] M. E. Sorge, W. H. Ailor, and T. J. Muelhaupt, "Space traffic management: the challenge of large constellations, orbital debris, and the rapid changes in space operations," *Aerosp. Corp.*, no. April 2021, pp. 187–195, Sep. 2020.

[105] C. Bonnal *et al.*, "Just in time collision avoidance—a review," *Acta Astronaut.*, vol. 170, pp. 637–651, May 2020, doi: 10.1016/j.actaastro.2020.02.016.

[106] R. Opromolla, G. Fasano, G. Rufino, and M. Grassi, "A review of cooperative and uncooperative spacecraft pose determination techniques for close-proximity operations," *Prog. Aerosp. Sci.*, vol. 93, pp. 53–72, Aug. 2017, doi: 10.1016/ j.paerosci.2017.07.001.

[107] R. W. Shepperd and K. C. DiOrio, “The time for a set of traffic rules has arrived,” presented at the AAS/AIAA Astrodynamics Specialist Conference, Aug. 2020.

[108] International Telecommunication Union, “International monitoring.” https://www.itu.int/en/ITU-R/terrestrial/monitoring/Pages/default.aspx (accessed May 04, 2021).

[109] J. Restrepo, “Radio Regulations,” presented at the 2018 ITU World Radiocommunication Seminar, Geneva, Switzerland, 2018. Accessed: May 04, 2021. [Online]. Available: https://www.itu.int/dms_pub/itu-r/md/15/wrs18/sp/R15-WRS18-SP-0003!!PDF-E.pdf

[110] International Telecommunication Union, “International Monitoring.” Accessed: May 04, 2021. [Online]. Available: https://www.itu.int/en/ITU-R/terrestrial/workshops/trainingCITEL/Documents/International%20Monitoring.pdf

[111] Space Data Association, “Welcome to the Space Data Association.” https://www.space-data.org/sda/ (accessed May 04, 2021).

[112] Alexander, Moss, McKissock, and Slatton, “U.S. Air Force fact sheet: 18th Space Control Squadron, processing reentries of space objects,” 18th Space Control Squadron, Vandenberg Air Force Base, California, Dec. 2020. Accessed: May 04, 2021. [Online]. Available: https://www.peterson.spaceforce.mil/Portals/15/Fact_Sheet_Processing_Reentries_of_Space_Objects_%20CAO_11Dec2020%20%28Final%29.pdf

[113] Peterson Air Force Base, “18th Space Control Squadron.” https://www.peterson.spaceforce.mil/About/Fact-Sheets/Display/Article/2356622/18th-space-control-squadron/ (accessed May 04, 2021).

[114] S. L. Dean, “email message to author,” Nov. 13, 2020.

[115] Federal Communications Commission, “Radio spectrum allocation.” [Online]. Available: https://www.fcc.gov/engineering-technology/policy-and-rules-division/general/radio-spectrum-allocation (accessed May 04, 2021).

[116] Federal Communications Commission, “EB - regional and field offices.” [Online]. Available: https://www.fcc.gov/eb-rfo (accessed May 04, 2021).

[117] Federal Communications Commission, “Enforcement primer.” [Online]. Available: https://www.fcc.gov/general/enforcement-primer (accessed May 04, 2021).

[118] United Nations Office for Outer Space Affairs, “Treaty on the Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies.” [Online]. Available: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html (accessed May 04, 2021).

[119] D. J. Trump, “Space Policy Directive-3, National Space Traffic Management Policy.” The White House, Jun. 18, 2018. Accessed: Apr. 27, 2021. [Online]. Available: https://trumpwhitehouse.archives.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/

[120] A. Console, “Command and Control of a Multinational Space Surveillance and Tracking Network,” *Jt. Air Power Competence Cent.*, p. 76, Jun. 2019.

[121] B. Weeden, “Space situational awareness fact sheet,” Secure World Foundation, May 2017. Accessed: May 04, 2021. [Online]. Available: https://swfound.org/media/205874/swf_ssa_fact_sheet.pdf

[122] K. Shimkus, “USSF announces initial operational capability, operational acceptance of Space Fence,” *United States Space Command*, Mar. 27, 2020. [Online]. Available: https://www.spacecom.mil/MEDIA/NEWS-ARTICLES/Article/2129356/ussf-announces-initial-operational-capability-operational-acceptance-of-space-f/

[123] National Aeronautics and Space Administration, “CARA: Conjunction Assessment Risk Analysis,” *Satellite Safety*. [Online]. Available: https://satellitesafety.gsfc.nasa.gov/cara.html (accessed May 04, 2021).

[124] 18th Space Control Squadron, “Spaceflight Safety Handbook for Satellite Operators,” Aug. 2020. [Online]. Available: https://www.space-track.org/documents/Spaceflight_Safety_Handbook_for_Operators.pdf

[125] D. S. McKnight *et al.*, “The global risk continuum (GRC),” *J. Space Saf. Eng.*, vol. 7, no. 1, pp. 38–43, Mar. 2020, doi: 10.1016/j.jsse.2020.01.002.

[126] Office of Commercial Space Transportation, “Towards a civil space traffic management system.” Accessed: May 04, 2021. [Online]. Available: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/6_space_traffic_management_plans.pdf

[127] M. Smith, “Office of Space Commerce wins bigger budget in FY2021, but will remain in NOAA,” *Space Policy Online*, Dec. 21, 2020. https://spacepolicyonline.com/news/office-of-space-commerce-wins-bigger-budget-in-fy2021-but-will-remain-in-noaa/

[128] J. N. Pelton, “Security concerns related to smallsats, space situational awareness (SSA), and space traffic management (STM),” in *Handbook of Small Satellites*, J. N. Pelton, Ed. Cham: Springer International Publishing, 2019, pp. 1–22. doi: 10.1007/978-3-030-20707-6_47-1.

[129] J. Foust, “How to better manage space traffic: aeolus/starlink encounter shows emails and late-night phone calls no longer cut it—spacenews,” *SpaceNews*, Nov. 21, 2019. https://spacenews.com/how-to-better-manage-space-traffic-aeolus-starlink-encounter-shows-emails-and-late-night-phone-calls-no-longer-cut-it/

[130] J. Foust, “ESA spacecraft dodges potential collision with Starlink satellite,” *SpaceNews*, Sep. 02, 2019. [Online]. Available: https://spacenews.com/esa-spacecraft-dodges-potential-collision-with-starlink-satellite/

[131] G. Peterson, M. Sorge, and W. Ailor, “Space traffic management in the age of new space,” Aerospace Corporation, Apr. 2018. Accessed: Apr. 28, 2021. [Online]. Available: https://aerospace.org/sites/default/files/2018-05/SpaceTrafficMgmt_0.pdf

[132] National Aeronautics and Space Administration, “NASA Technical Standard: Process for limiting orbital debris,” NASA-STD-8719.14B, Apr. 2019. [Online]. Available: https://standards.nasa.gov/file/15794/download?token=Ju0FqNhW

[133] National Aeronautics and Space Administration, “Deorbit systems,” Nov. 27, 2020. [Online]. Available: https://www.nasa.gov/smallsat-institute/sst-soa-2020/passive-deorbit-systems/

[134] T. Maclay and D. McKnight, “Space environment management: Framing the objective and setting priorities for controlling orbital debris risk,” *J. Space Saf. Eng.*, vol. 8, no. 1, pp. 93–97, Mar. 2021, doi: 10.1016/j.jsse.2020.11.002.

[135] D. McKnight and T. Maclay, “Space environment management: A common sense framework for controlling orbital debris risk,” presented at the 2019 Advanced Maui Optical and Space Surveillance Technologies Conference, 2019. [Online]. Available: https://amostech.com/TechnicalPapers/2019/Orbital-Debris/McKnight.pdf

[136] D. McKnight, “email message to author,” Nov. 18, 2020.

[137] National Oceanic and Atmospheric Administration, “OSC OADR Industry Day Slidedeck NOV2020,” Nov. 23, 2020. [Online]. Available: https://govtribe.com/file/government-file/docnoaafy21oscspd3openarchitecturedatarepository-osc-oadr-industry-day-slidedeck-nov2020-dot-pdf

[138] D. L. Oltrogge, “The ‘we’ approach to space traffic management,” presented at the 2018 SpaceOps Conference, Marseille, France, May 2018. doi: 10.2514/6.2018-2668.

[139] M. R. Migaud, “Policy tools for preventing, mitigating, and defending against orbital debris,” presented at the International Orbital Debris Conference, Sugar Land, TX, USA, Dec. 2019. [Online]. Available: https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6103.pdf

[140] Driving Laws, “Driver’s License Point Systems.” [Online]. Available: https://www.drivinglaws.org/topics/drivers-license-point-systems (accessed May 14, 2021).

[141] D. McKnight, *Space traffic management: Do not build on a weak foundation*. 2020. [Online]. Available: https://ecfsapi.fcc.gov/file/11040708229215/FCC%2018_313%20response%20McKnight%204NOV2020.pdf

[142] T. Hitchens, “Fearing isolation, Russia caves on UN pace guidelines,” *Breaking Defense*, Jun. 25, 2019. https://breakingdefense.com/2019/06/fearing-isolation-russia-caves-on-un-satellite-guidelines/

[143] Aerospace Technology, “The 10 countries most active in space,” Dec. 21, 2015. [Online]. Available: https://www.aerospace-technology.com/features/featurethe-10-countries-most-active-in-space-4744018/

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California